Planetary Debris Disks: From IRAS and 2MASS to SIRTF and TPF

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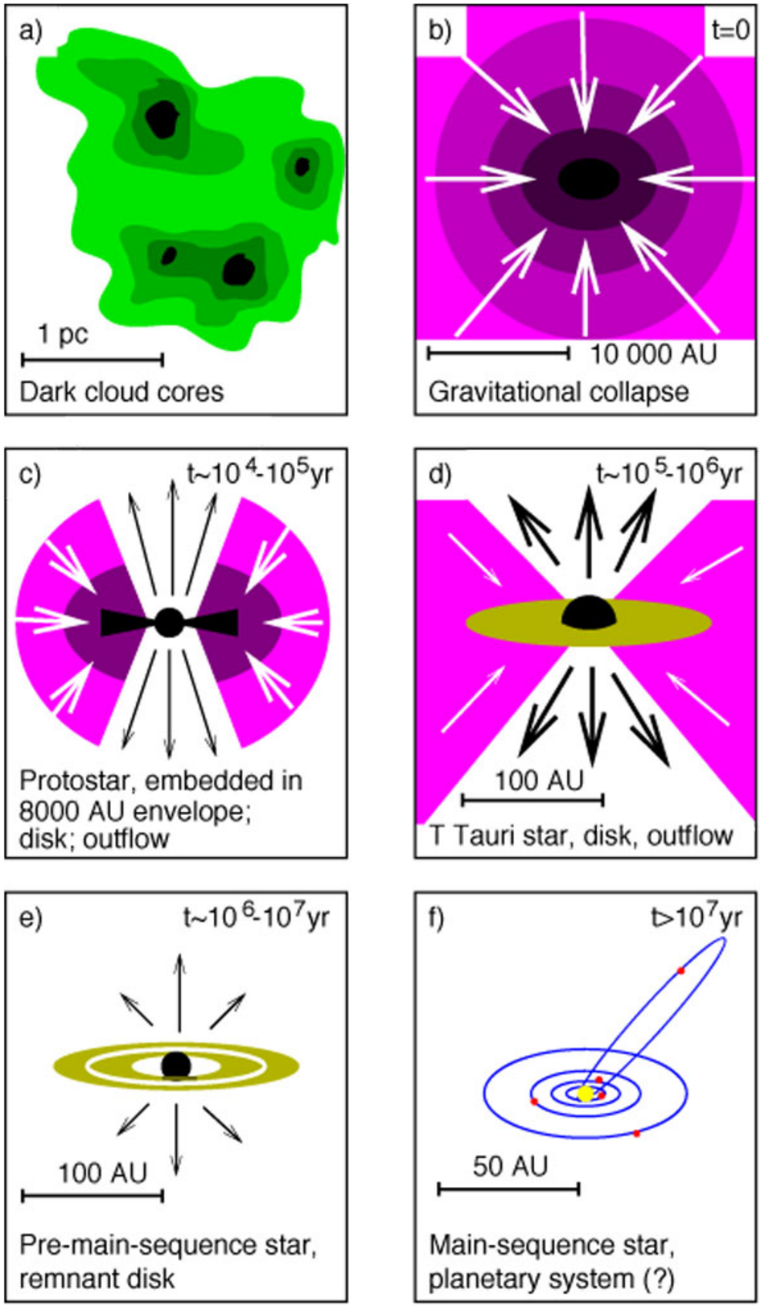
24 August, 2000

Disks (and Planets?) Are an Integral Part of the Star Formation Process

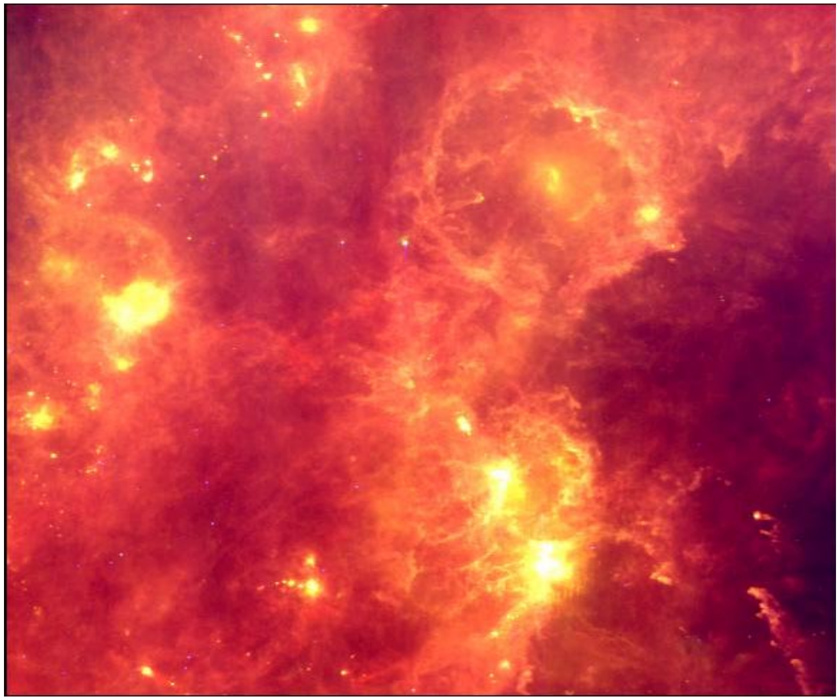


Hogerheijde 1998, after Shu et al. 19

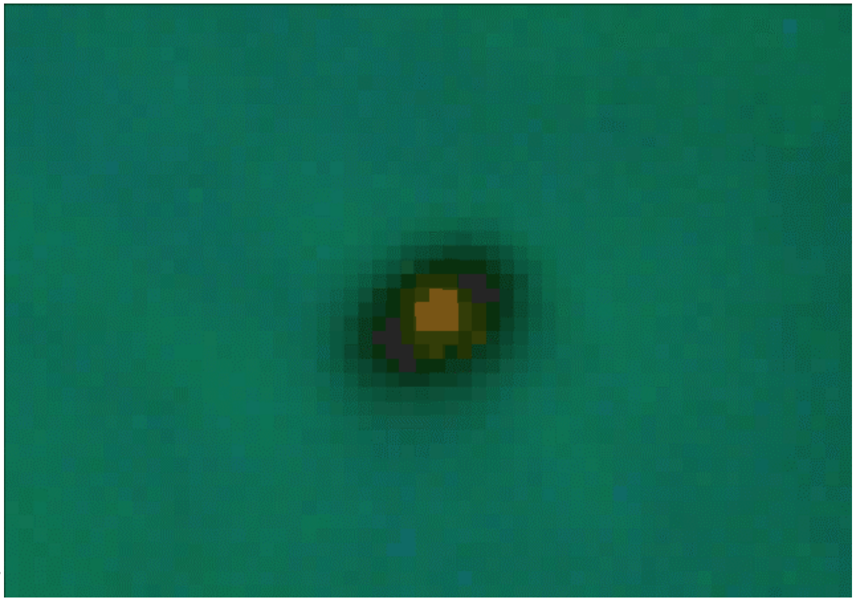
Unanswered Questions

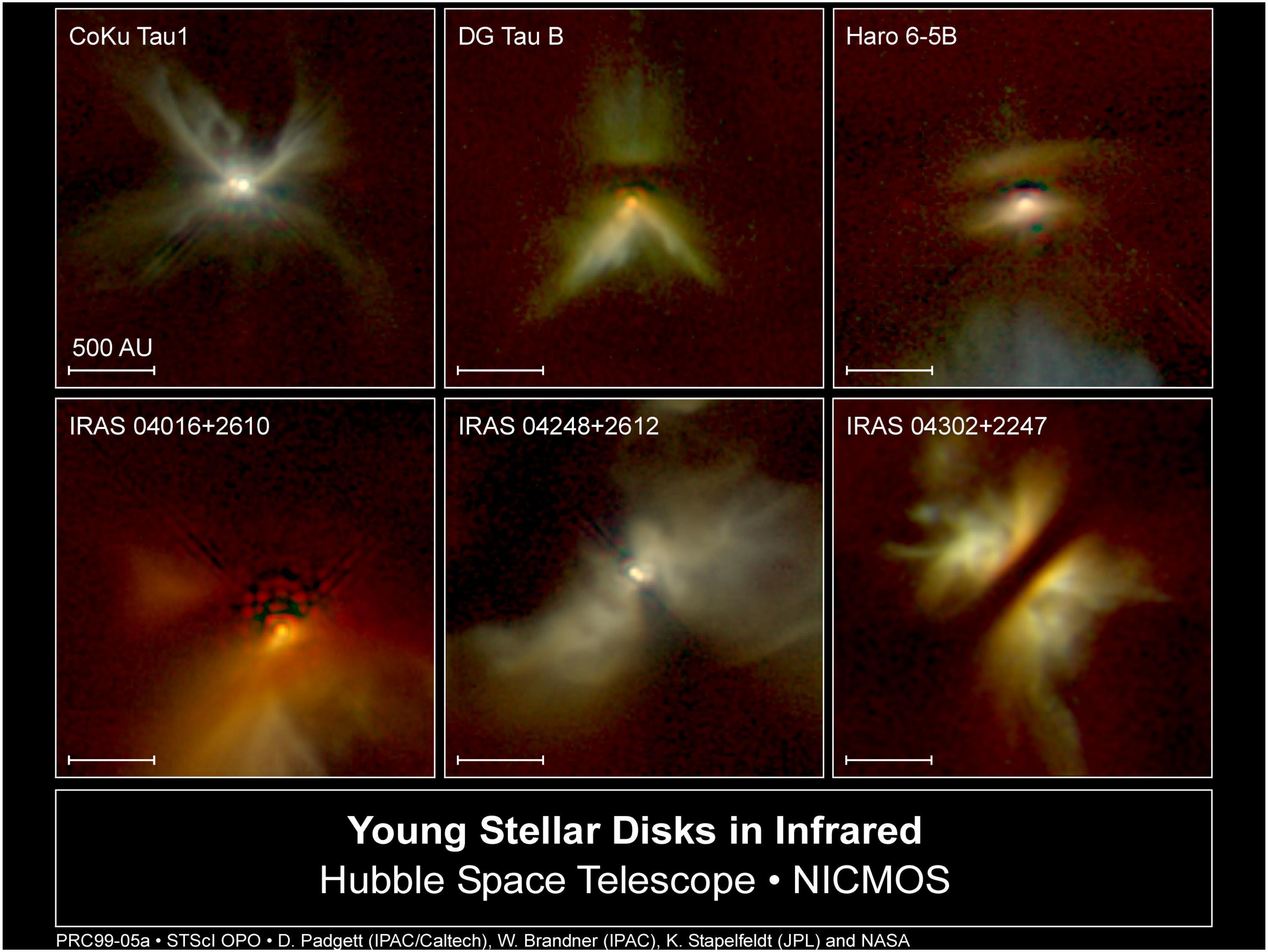
- How does disk content (gas and dust) and structure evolve as star evolves?
  - What is timescale for planet formation?
- What is distribution of material?
  - Inner and outer extent
  - Kuiper Belt vs. zodiacal dust cloud
- What processes create the observed structures?
  - Planets --- by analogy with planetary ring systems?
  - Stellar Interactions?
- What is nature of material
  - Dust size and composition = f(r,t)
- Are there systems "clean" enough where we can find planets?

Disks Around Young Stars



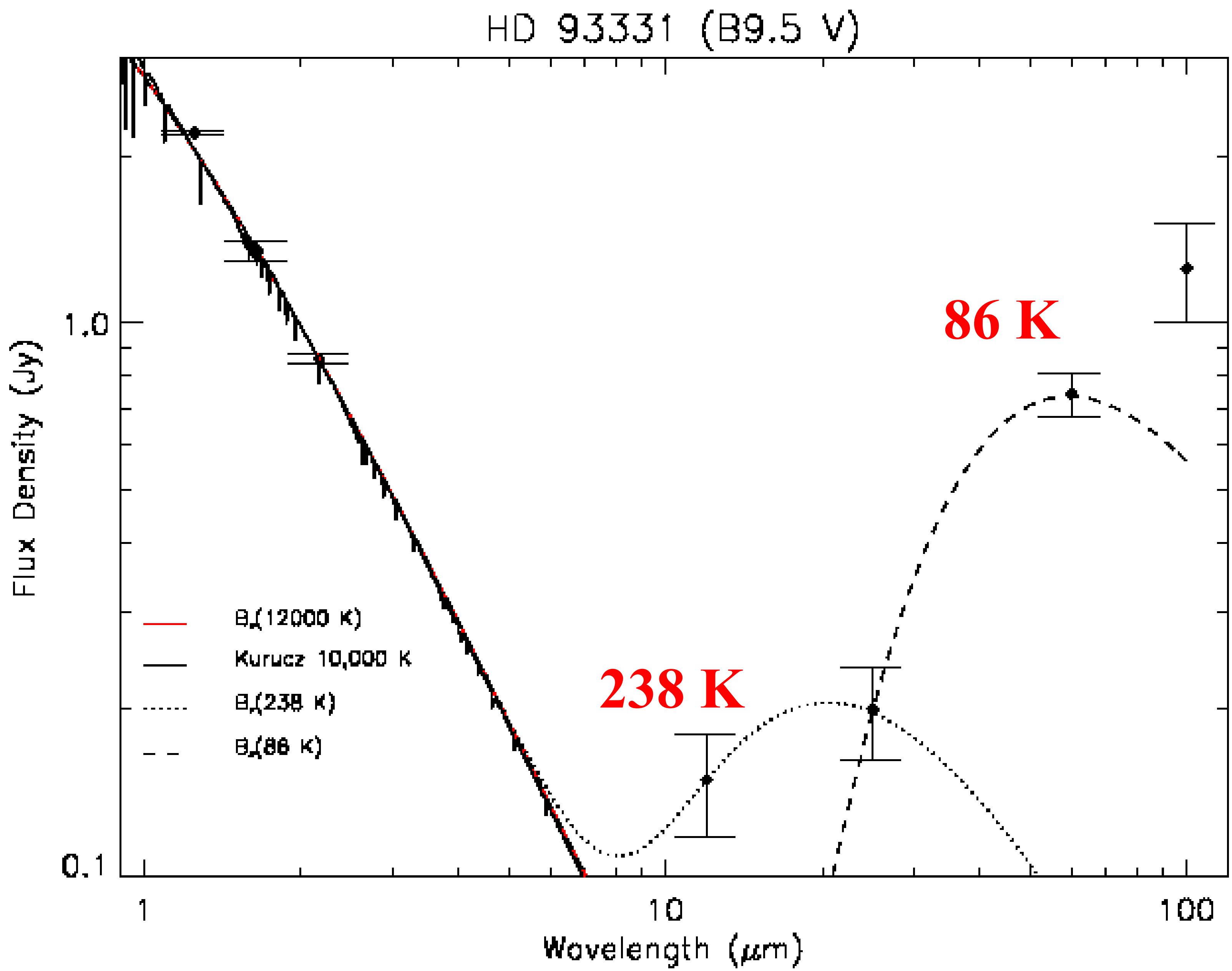
- Mid-, far-IR, submillimeter excess, and in millimeter lines with Keplerian Rotation
- In absorption and scattered light on scale of few 100 AU
- Mass 0.01~0.1 M_o




CoKu Tau1
500 AU
DG Tau B
Haro 6-5B
IRAS 04016+2610
IRAS 04248+2612
IRAS 04302+2247
Young Stellar Disks in Infrared
Hubble Space Telescope • NICMOS
PRC99-05a • STScI OPO • D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL) and NASA

Disks Around Mature Stars

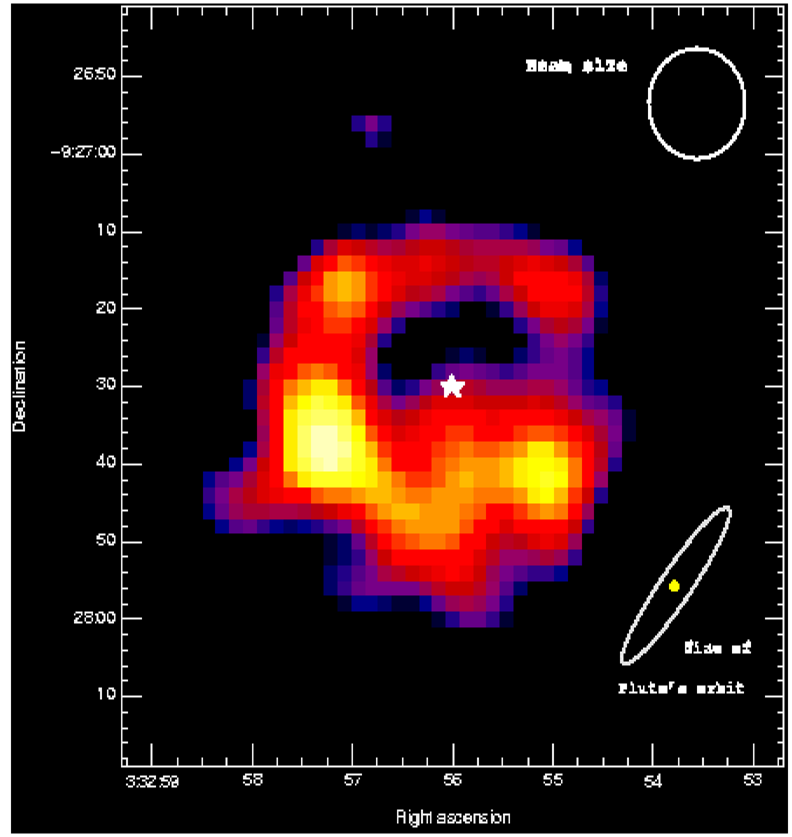
- IRAS found ~15% of main sequence stars showed excess
  - Vega, β Pictoris, α PsA, ε Eri are the "Big 4"
  - Typical IRAS star has τ~10^{-3} (β Pic)~ to 10^{-4} (Vega)
  - Selection effects favor early type stars (A-F stars)
- Most excesses at $\lambda \geq 60$ μm consistent with remnant Kuiper Belt material at 10s-100s of AU (as predicted pre-IRAS by Witteborn *et al* 1982, Icarus, 50, 63)
  - A few stars resolved by IRAS/ISO, mostly inferences from inverting SED, $F(\nu) \rightarrow T(r)*\rho(r)$
  - Loss mechanisms imply reservoir of Lunar-Earth (?) mass of 0.1 mm (?) dust grains at 60-100 K
- Only a few % of stars have excess at $\lambda \geq 12$ μm, corresponding to "zodiacal" dust: β Pic and HR 4796 are prime examples.
  - Origin in asteroid collisional debris and/or cometary ejecta



HD 93331 (B9.5 V)
Flux Density (Jy)
Wavelength (μm)
1.0
0.1
1
10
100
Bλ(12000 K)
Kurucz 10,000 K
Bλ(238 K)
Bλ(86 K)
86 K
238 K

Physical Properties of ε Eri Disk

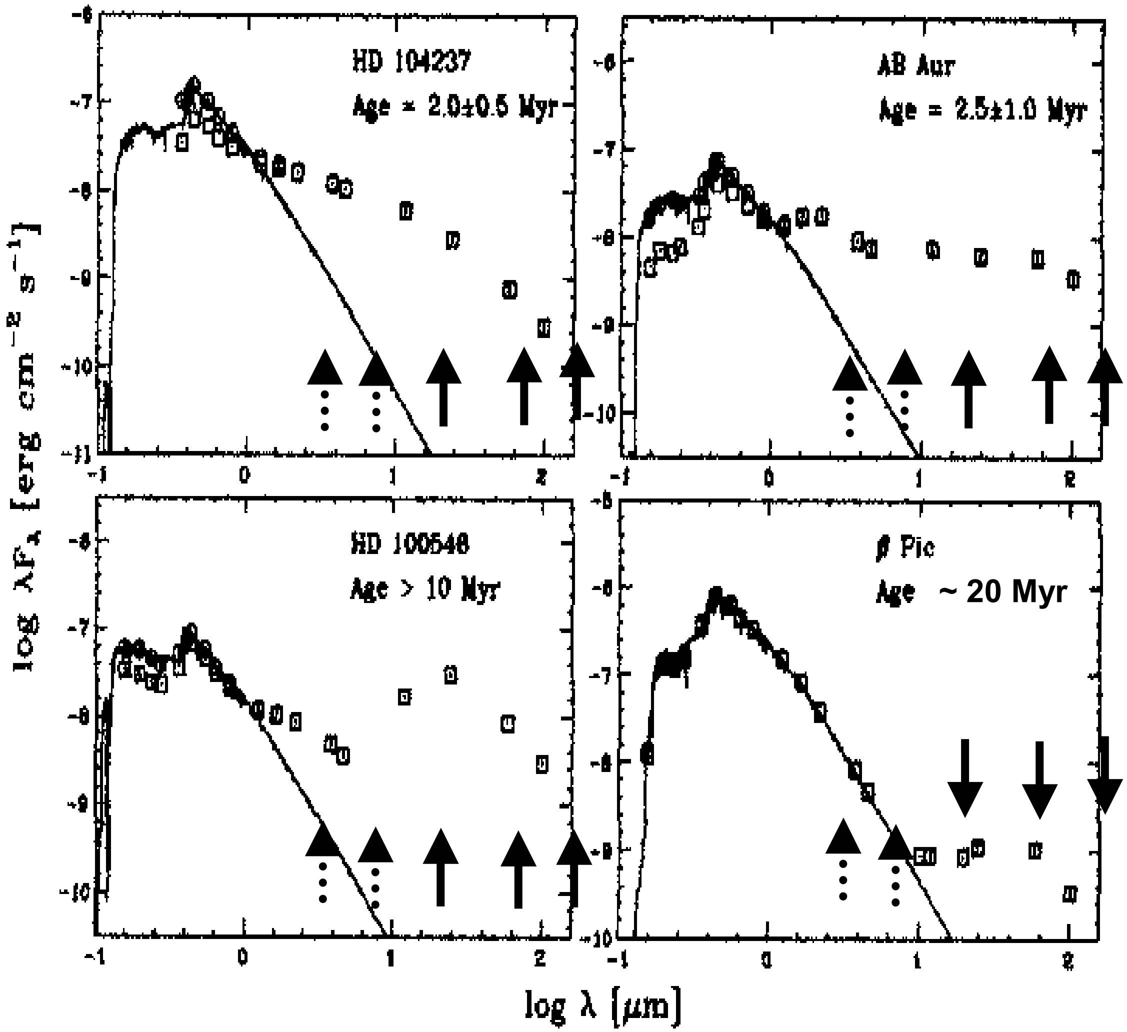
- ε Eri is young (1 Gyr) K2V main sequence star 3.3 pc away
- 850 μm SCUBA/JCMT maps resolve disk showing peak emission at 60 AU with hole at 30 AU
  - Scale corresponds to Neptune's orbit and Kuiper Belt zone (30-100 AU) in our solar system
- Mass of dust > 0.01 $M_{\oplus}$ ($\propto$grain size)
  - Comparable to mass of comets in solar system (0.04-0.3 $M_{\oplus}$)
  - Limit of 0.4 $M_{\oplus}$ to gas (CO)
- Asymmetries (?) due to outer planets (in addition to Jupiter at ~ 3AU) or observational uncertainties



Graeves *et al.* 1998

Massive Disks Dissipate Rapidly

- IR excess drops rapidly with age leaving residual at long λ after 10^7 yr.
- Useful metric is τ~Ldust/Lstar ~ surface optical depth
  - τ~ 10^{-2} for young protostars, TT stars
  - τ~ 10^{-7} for the Sun

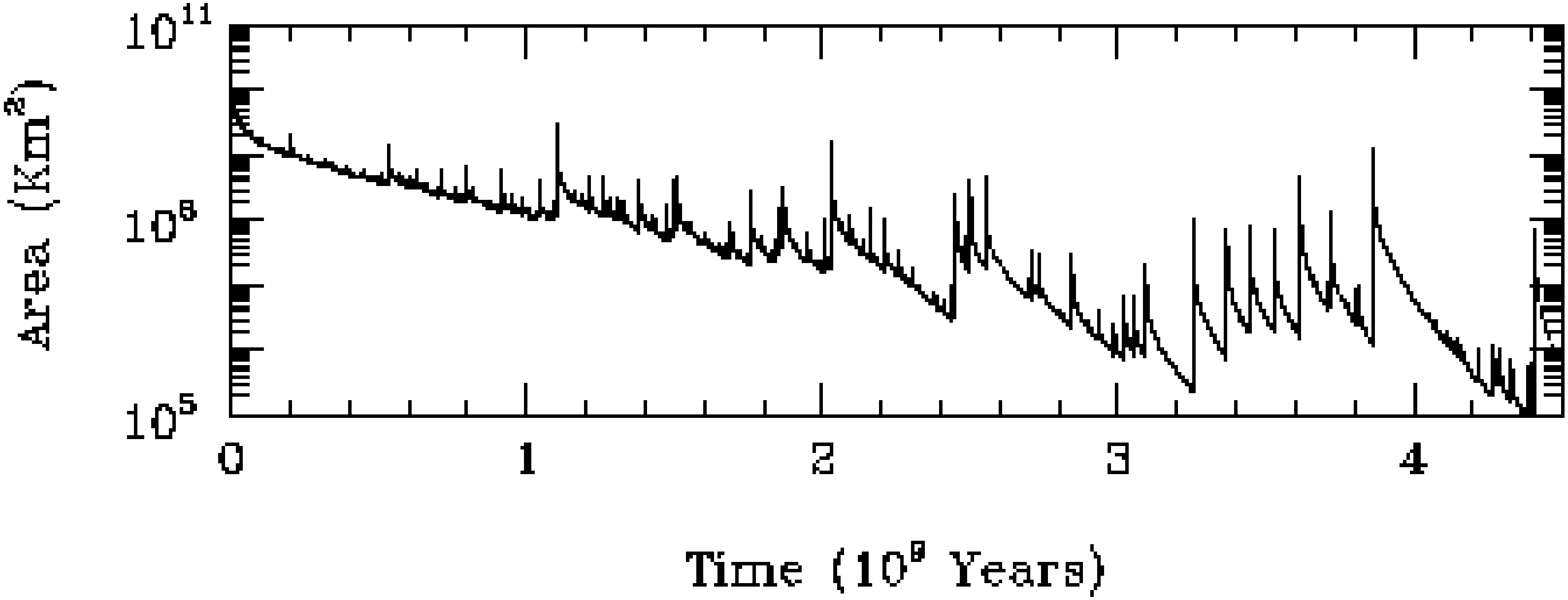


Van den Anker *et al*., A&AL, 324, L33

Evolution of Gas in Disks

- Near-IR excess, millimeter CO, and near-IR CO are common tracers for (hot) gas in young disks (Hillenbrand and Meyer 1999)
- Gas and hot disks disappear on timescales of 10-20 Myr, although depletion of gas onto grains or disassociation of CO by ISRF may by VERY misleading
- Thi *et al.* (IAU 2000) found H_2 around 3 debris stars (49 Cet, HD 135344 and β Pictoris) with approximately 100:1 ISM ratio
- This timescale is (barely) consistent with formation of giant planets
  - Theory and observations are quite flexible

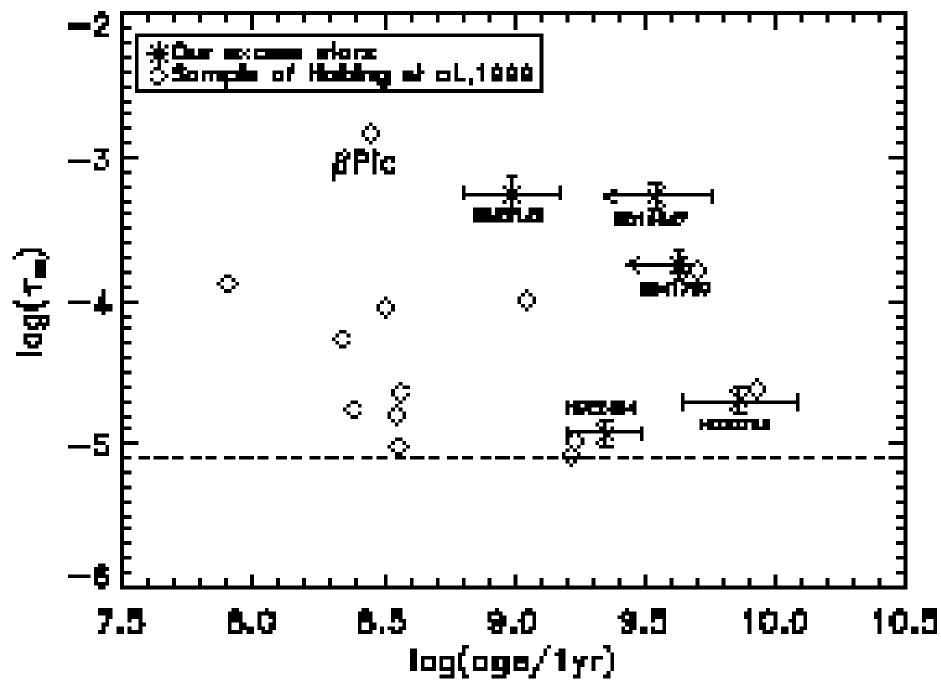
Evolution of Solids in Disks



- Collisional cascade of material into small grains that are then lost to solar system by radiation pressure (out of solar system) or Poynting-Robertson drag (into Sun)
- Issues include size and location of reservoir (Kuiper Belt)

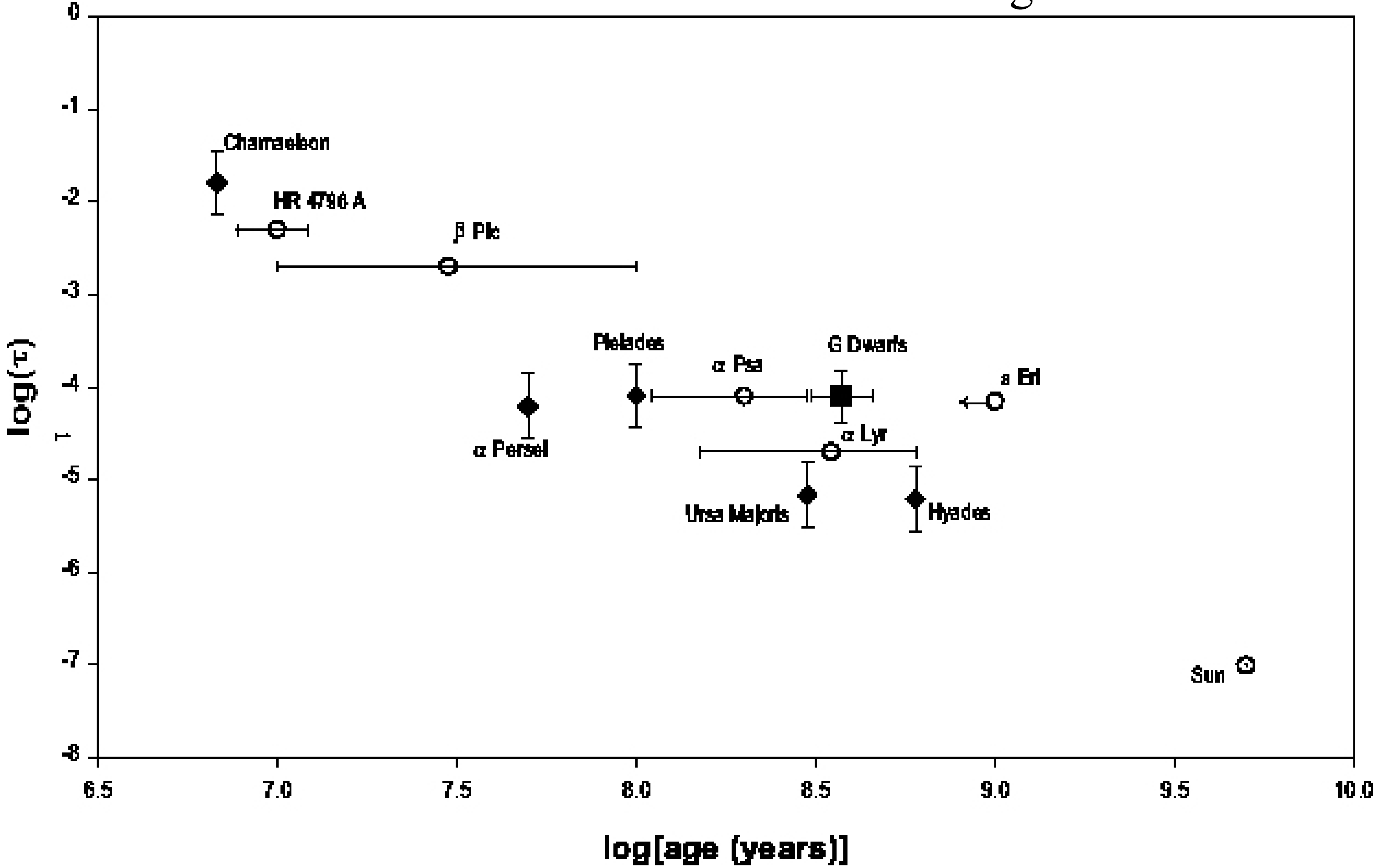
Conflicting Results on Disk Evolution

- Habing *et al* (1999) suggest disks disappear rapidly after 400 Myr
  - >50% of A-F stars younger than 300 MYr have 25-70 µm excesses
  - <8% of older stars have disks
- Decin *et al 2000* find excesses around 3-5(?) of 30 G dwarfs (3 Gyr)
- Problems may include ISO calibration, stellar ages, intrinsic variation of initial disk mass and dissipation mechanisms

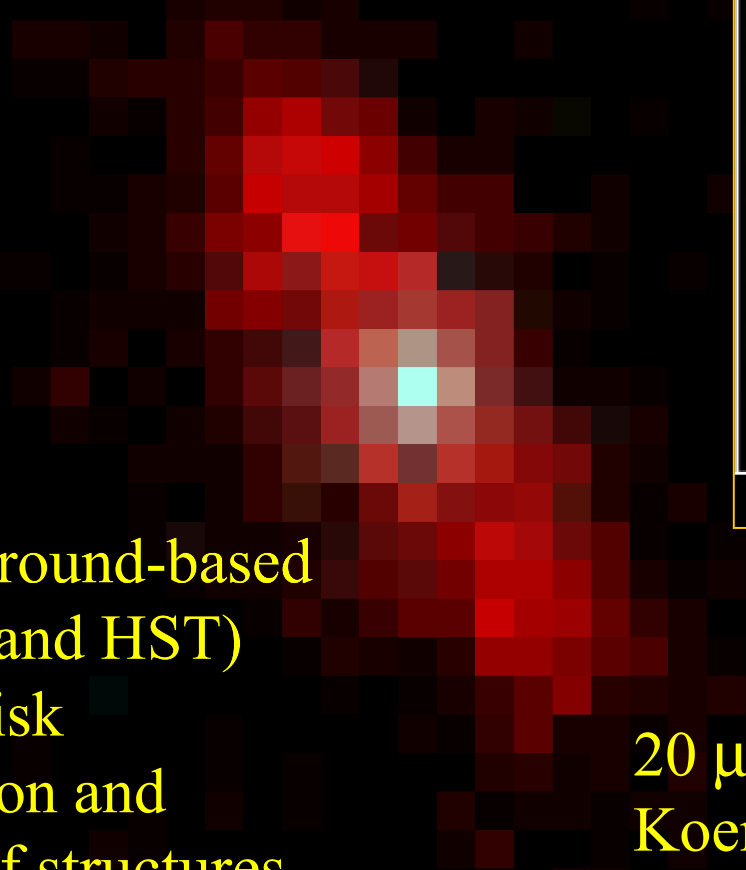


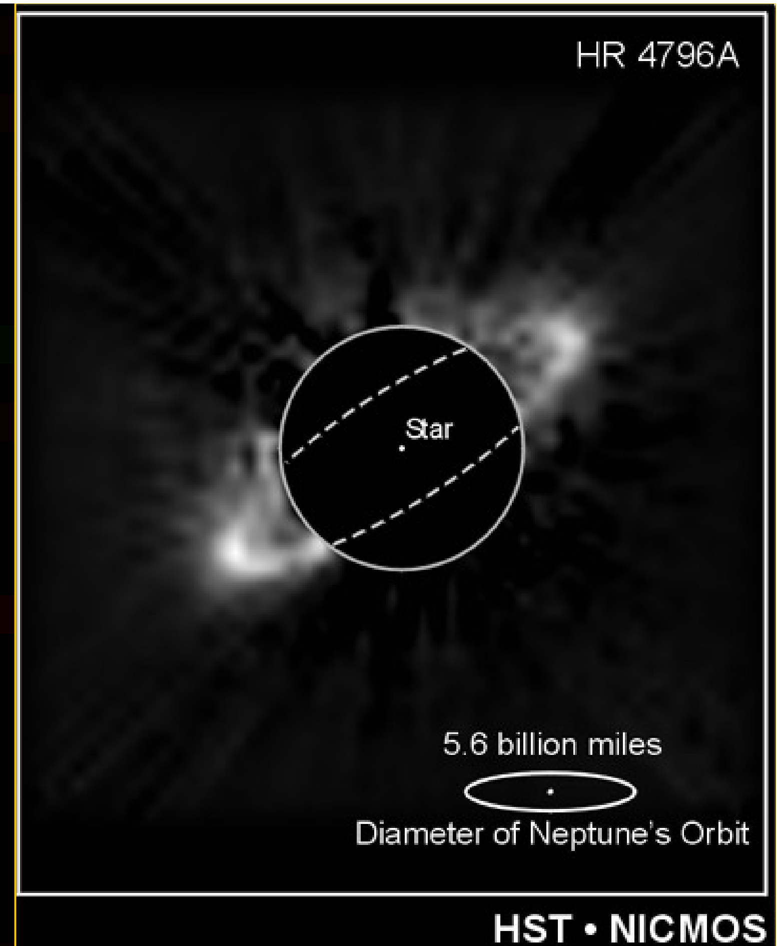
G. Decin, C. Dominik, K. Malfait, M. Mayor, and C. Waelkens 2000, A&A, 357, 533.

Weinberger *et al* 1999



Direct Imaging of HR 4796 Reveals Disk





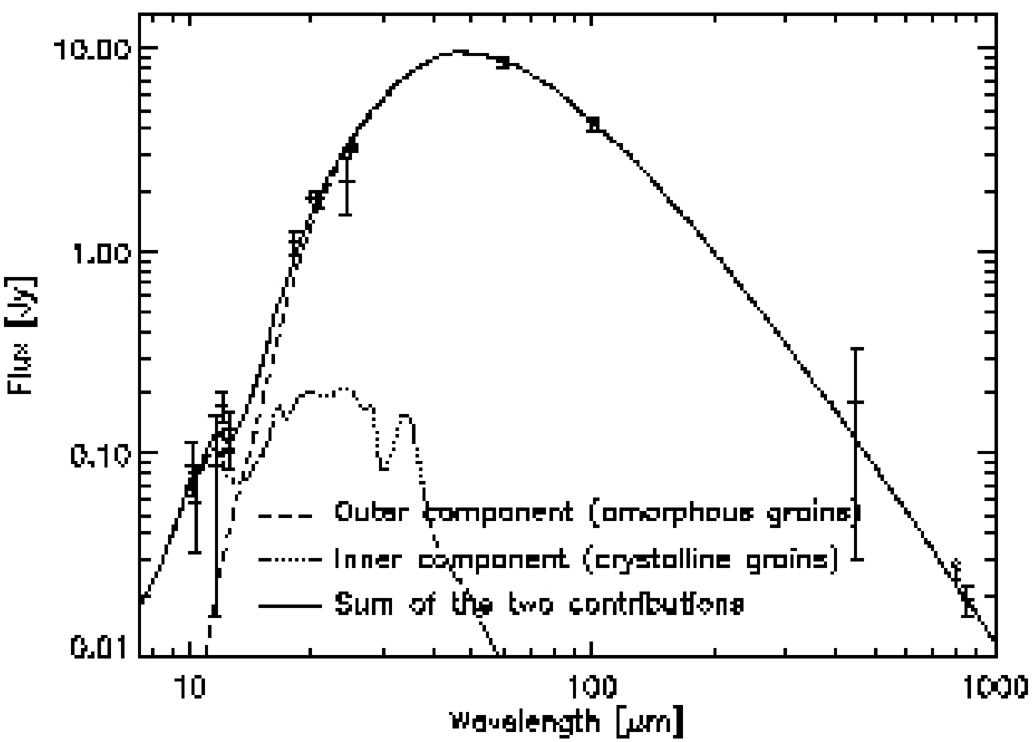
- Imaging (ground-based telescopes and HST) confirms disk interpretation and existence of structures (gaps, warps, and blobs)

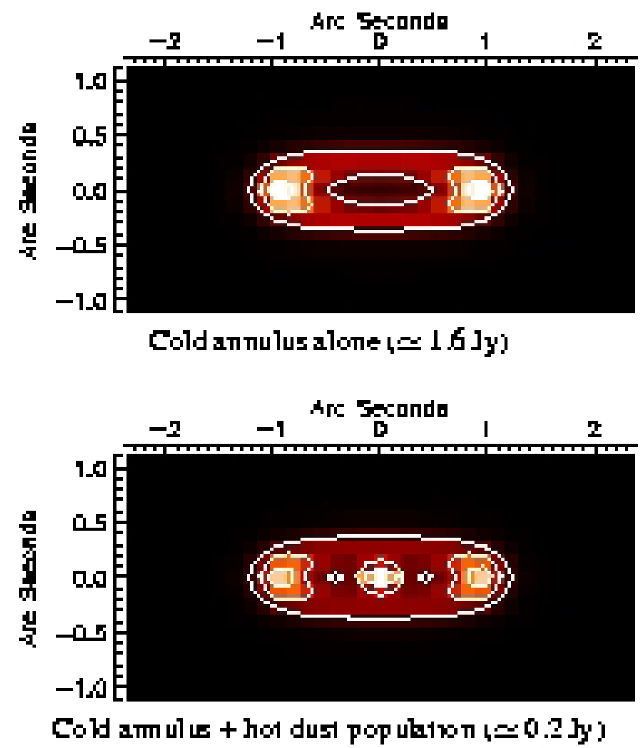
20 μm image from Koerner, *et al.* 1998 ApJ, 503, L83.

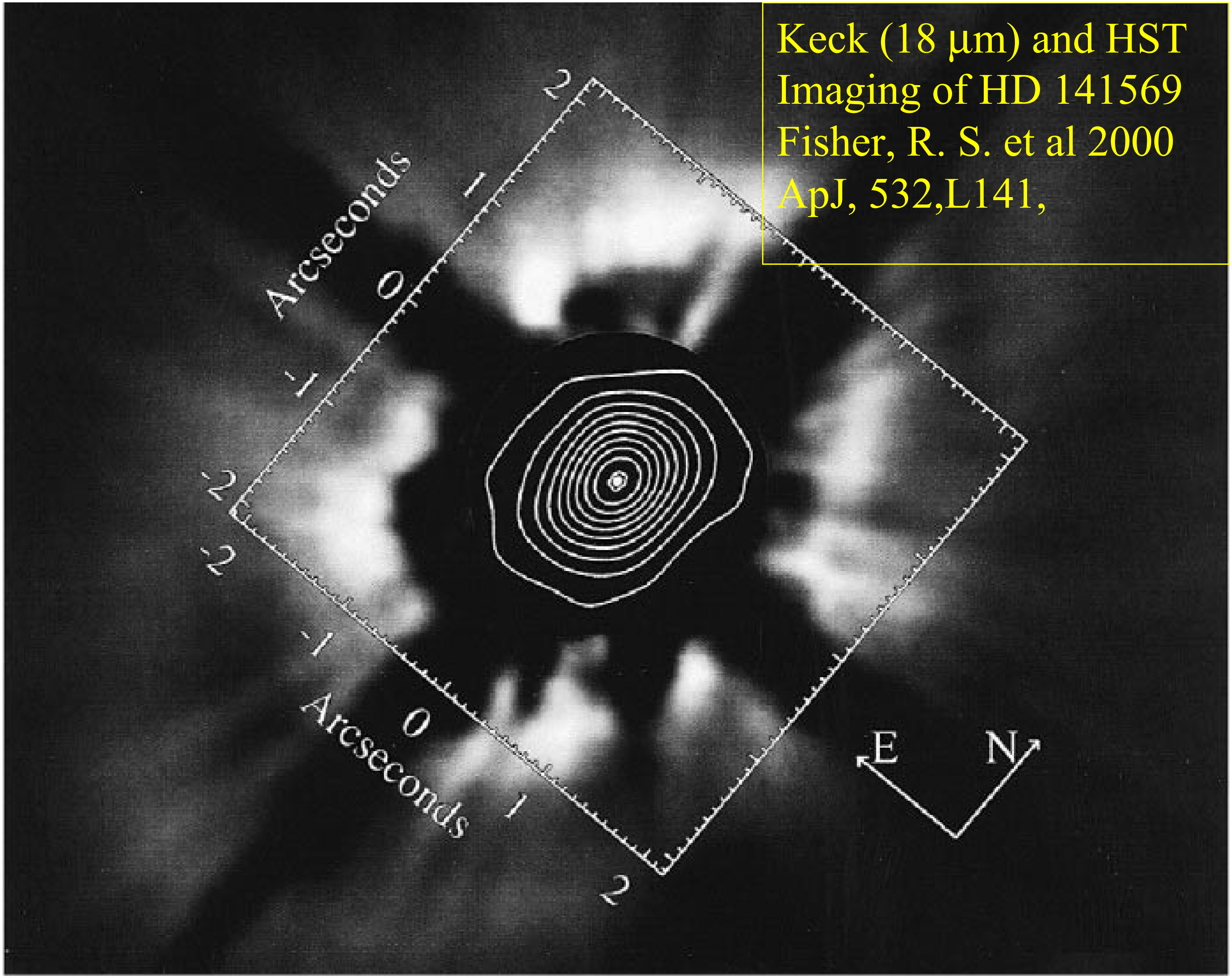
HR 4796 Has 2 Dust Components

- Large (10 um), ISM-composition grains in 70 AU annulus. Bodies as large as a few meters with total mass of >1 Earth Mass
- Smaller, hot crystalline (cometary) grains around 9 AU from star

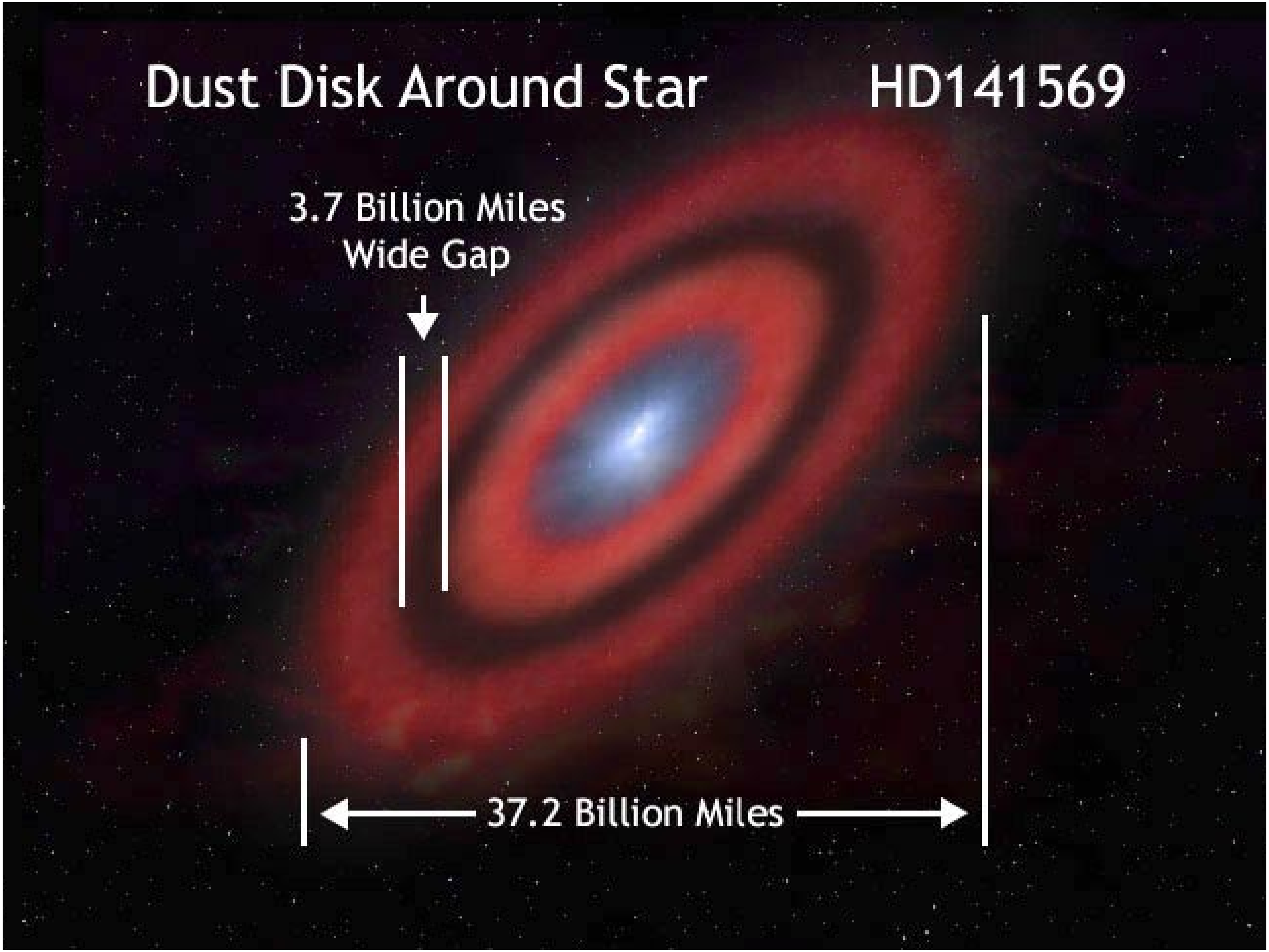
Augereau et al 1999, A&A, 348,557



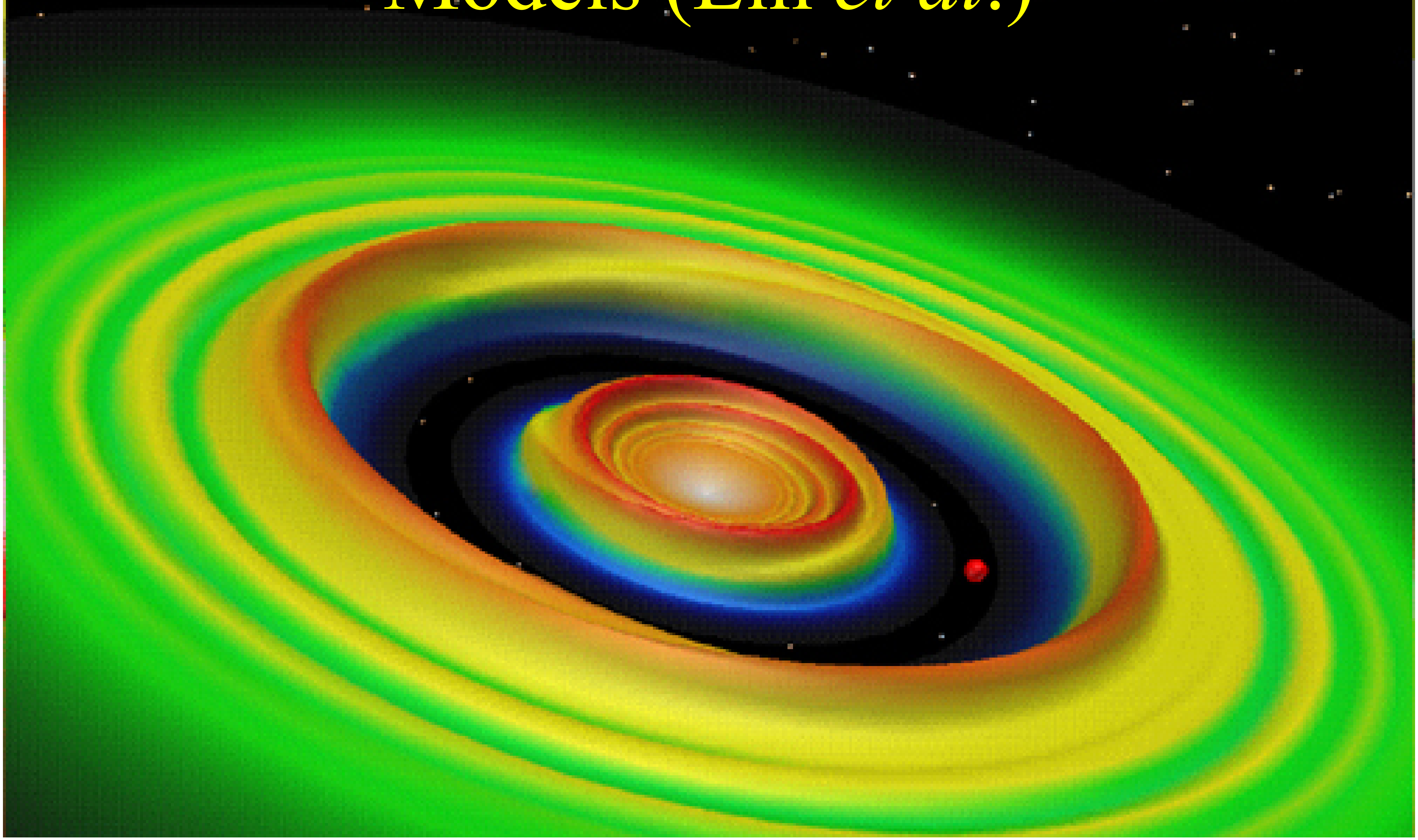


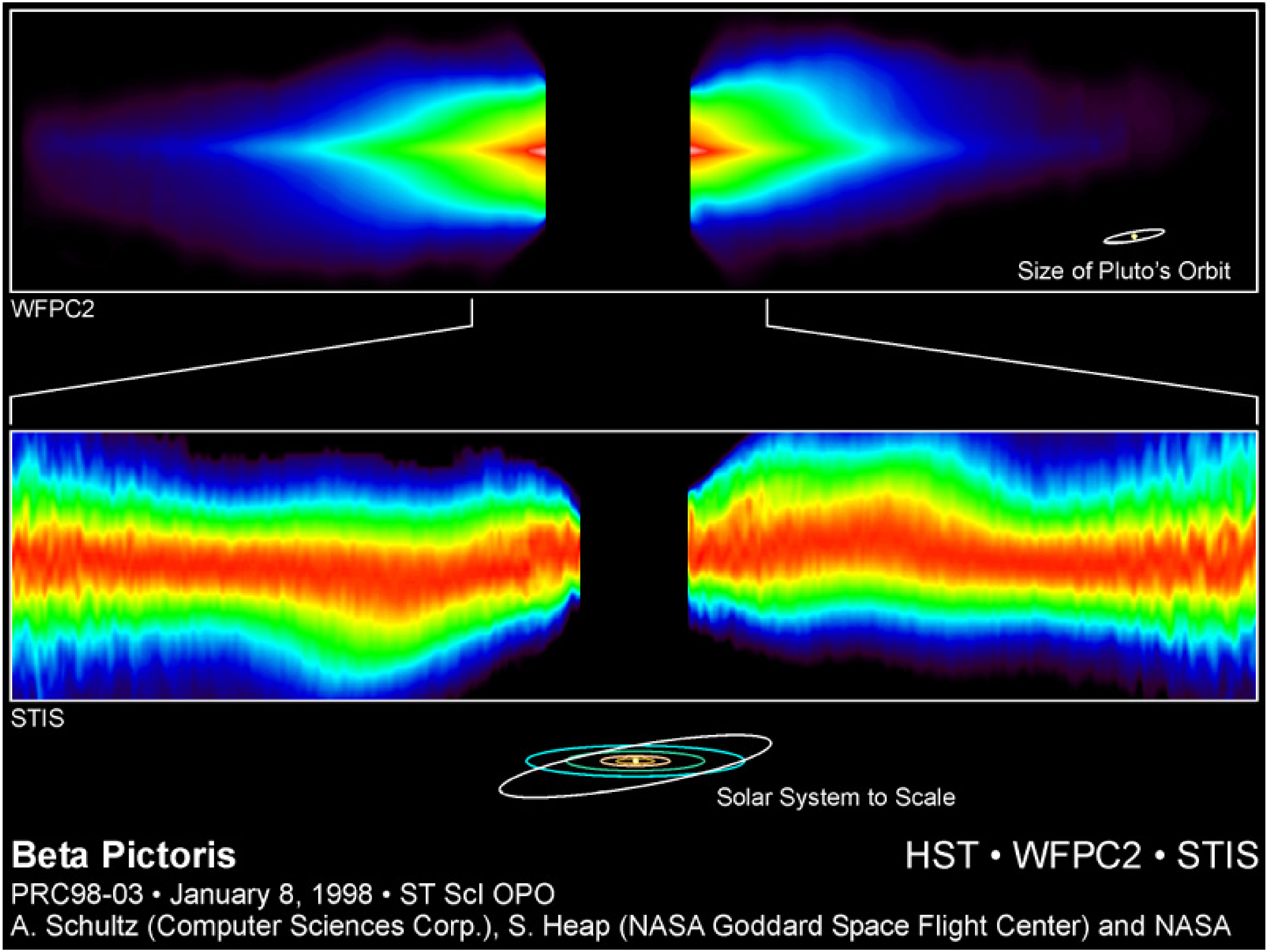


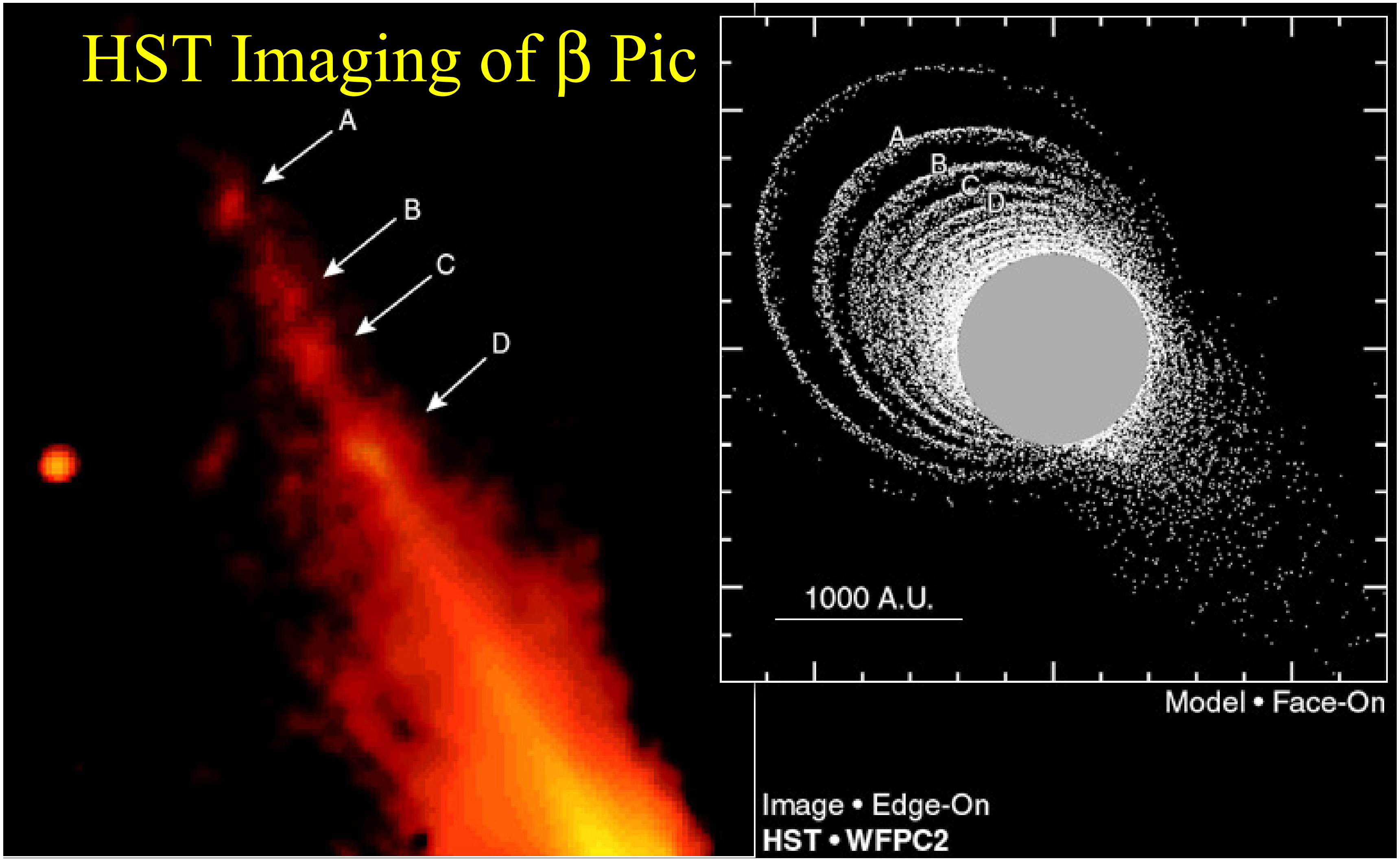
Keck (18 μm) and HST
Imaging of HD 141569
Fisher, R. S. et al 2000
ApJ, 532,L141,


Dust Disk Around Star
HD141569
3.7 Billion Miles
Wide Gap
37.2 Billion Miles

Planets Open Gaps in 3-D Disk Models (Lin *et al.*)

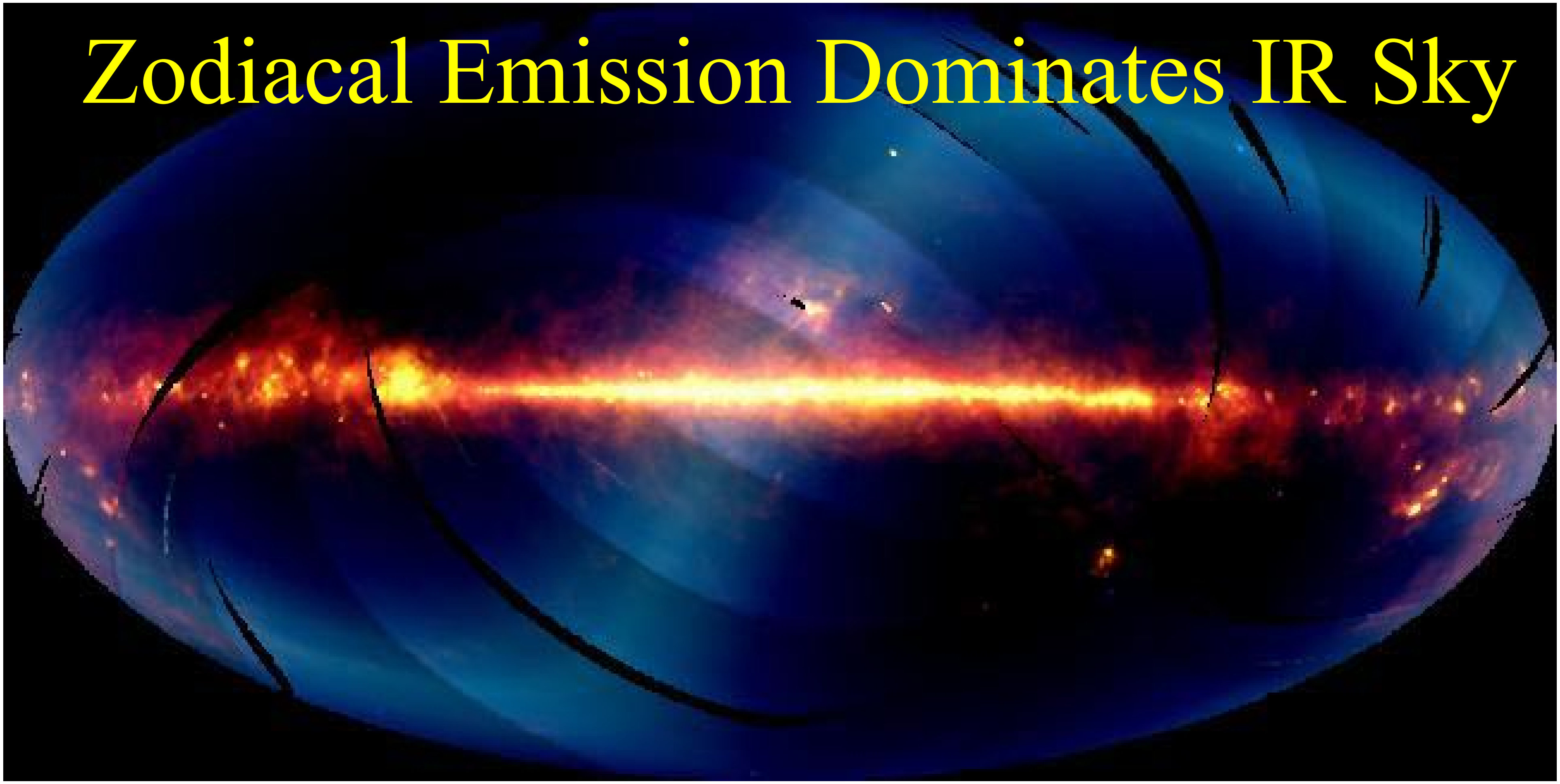



Size of Pluto's Orbit
WFPC2
STIS
Solar System to Scale
Beta Pictoris
HST • WFPC2 • STIS
PRC98-03 • January 8, 1998 • ST ScI OPO
A. Schultz (Computer Sciences Corp.), S. Heap (NASA Goddard Space Flight Center) and NASA



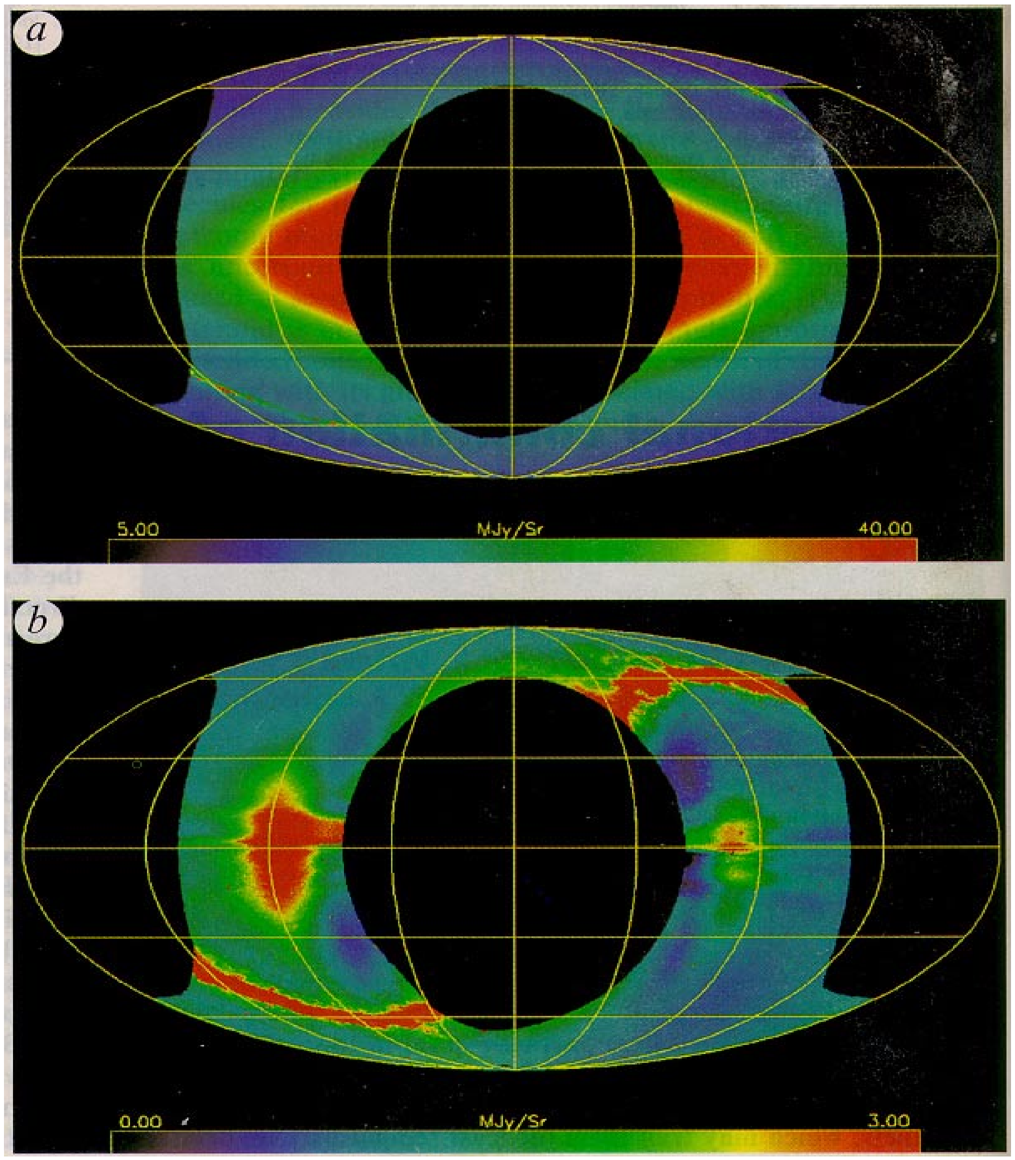
- Gaps, warps, and condensations variously interpreted as due to interior planets, stellar passage
- Variable spectral lines interpreted as cometary infall

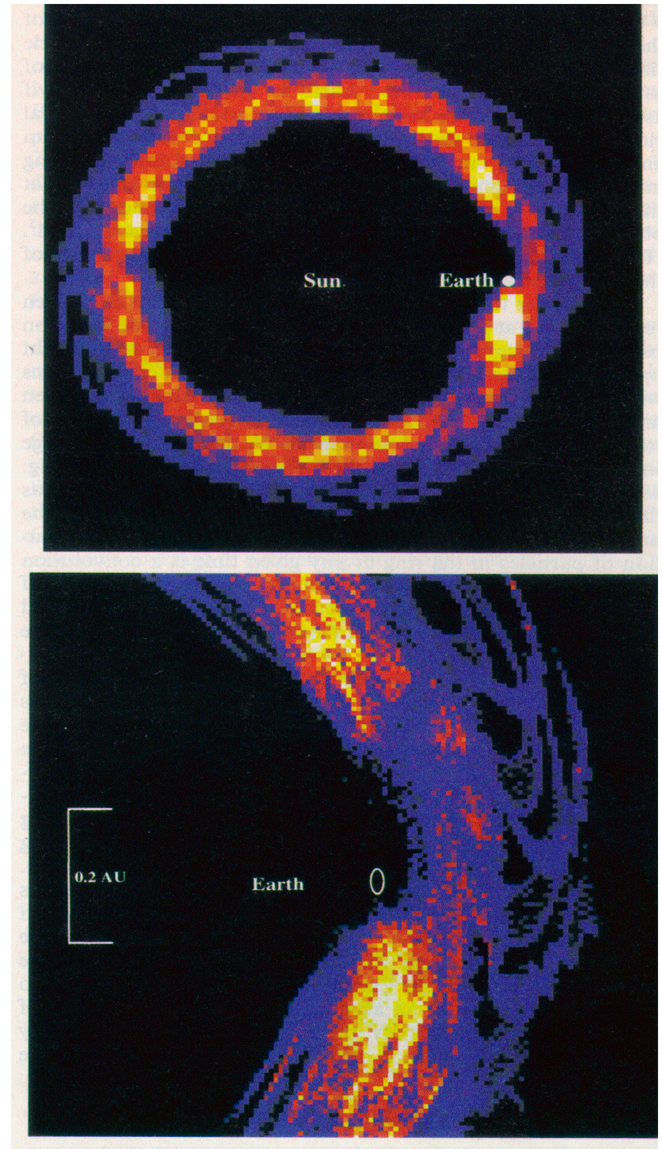
Zodiacal Emission Dominates IR Sky



- Our own solar system is dominated by a zodiacal dust cloud composed mostly of material created in asteroidal collisions, drifting inward to Sun due to Poynting-Robertson drag

Wakes in Solar System Dust Cloud due to Planets



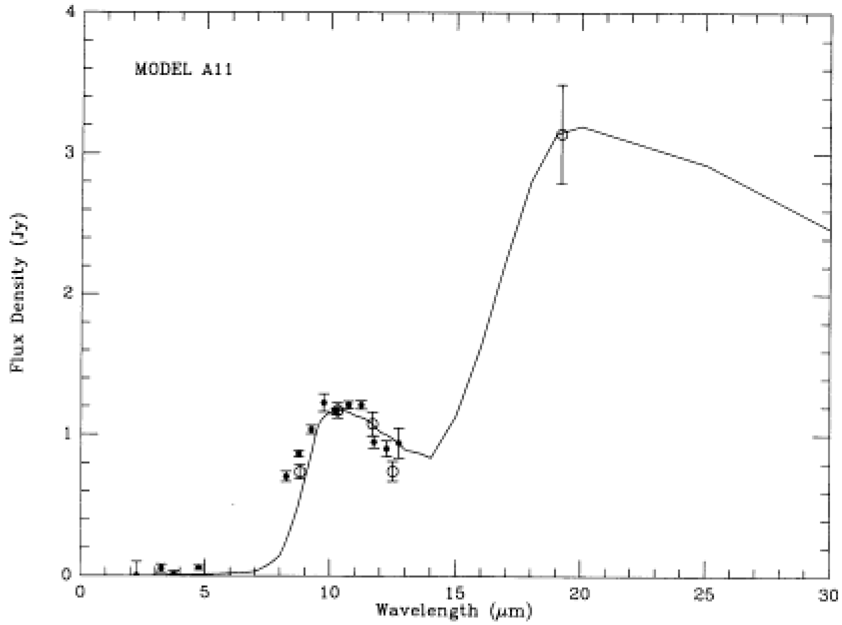


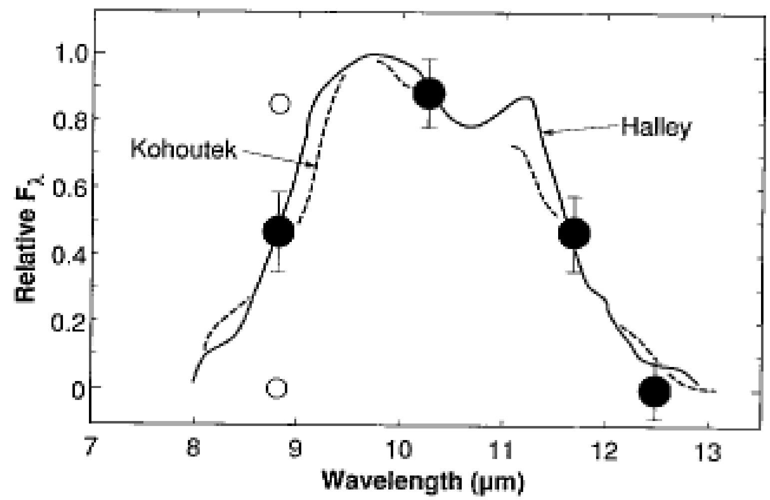
Reach et al 1995; Dermott et al. 1998

Relative Strength Of Sources Of Zodiacal Dust Near The Earth

Main Belt Asteroid Collisions	50-90 %
Comet Activity And Collisions	10-50 %
Trojan Asteroids	minor
Kuiper Belt Planetesimals	minor
ISM Grains	~ 0.1 %

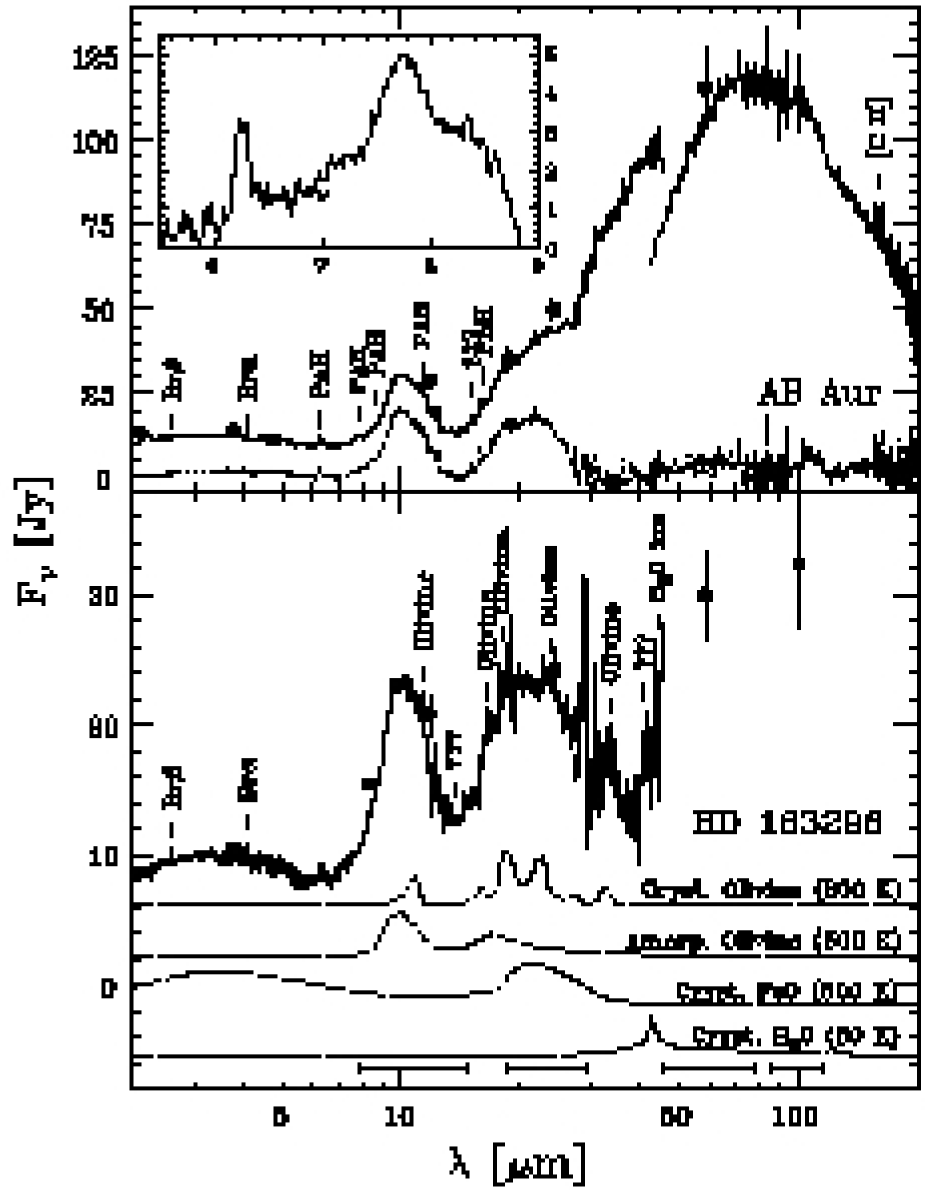
Only Limited Information On Dust Composition





Integrated dust model suggests ~1 μm *silicate* grains orbiting out to 140 AU around β Pic. (Knacke *et al.* 1993 ApJ., 418, 440)

Spectrum of Massive Disk Extends Solar System Analogy



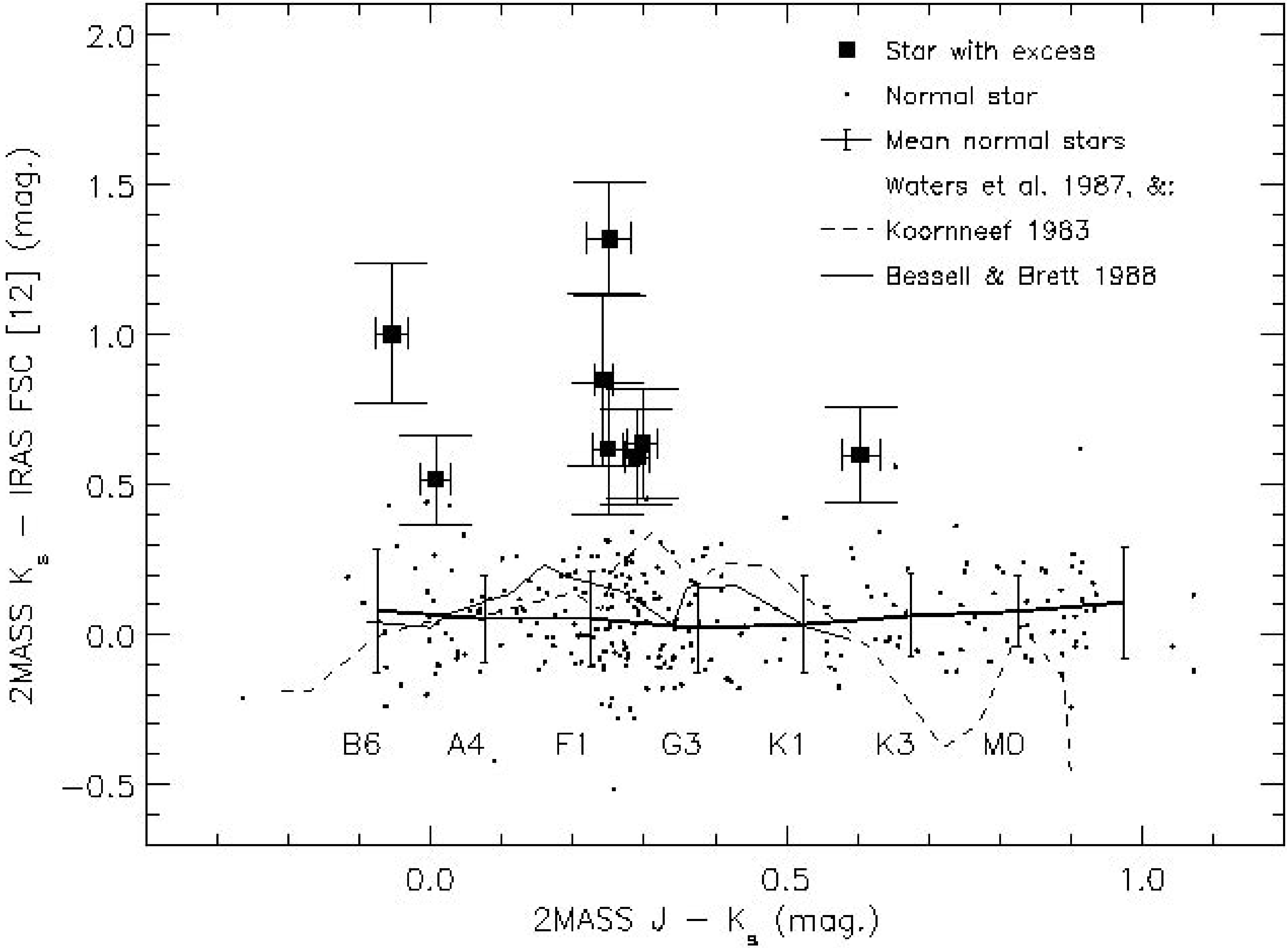
- ISO spectrum of AB Aur requires combination of forsterite, olivine, PAHs, FeO, H_2O ice (40, 69 μm) Van Ancker *et al* A&A, 357, 325-329 (2000)
- Spectrum similar to Hale-Bopp's (Crovisier *et al.* 2000)

2MASS Search for Hot Excess

- Incidence of HOT dust clouds is low (<5% of all stars)
  - Habitable zone dust clouds, not Kuiper Belt analogs
- 2MASS/IRAS cross comparison for 296 main sequence stars
  - with Sergio Fajardo-Acost & Roc Cutri
- 2MASS photometry is accurate enough and the extrapolation to longer wavelengths simple enough that cross correlation with IRAS (now) and SIRTF surveys (in the future) will reveal many more disk systems
- Identified 8 new hot zodiacal clouds based on 12 μm excess relative to extrapolation of 2MASS photometry
  - Adds to 14 previously know systems
  - Projecting 50~100 new systems when entire 2MASS/IRAS sky is examined

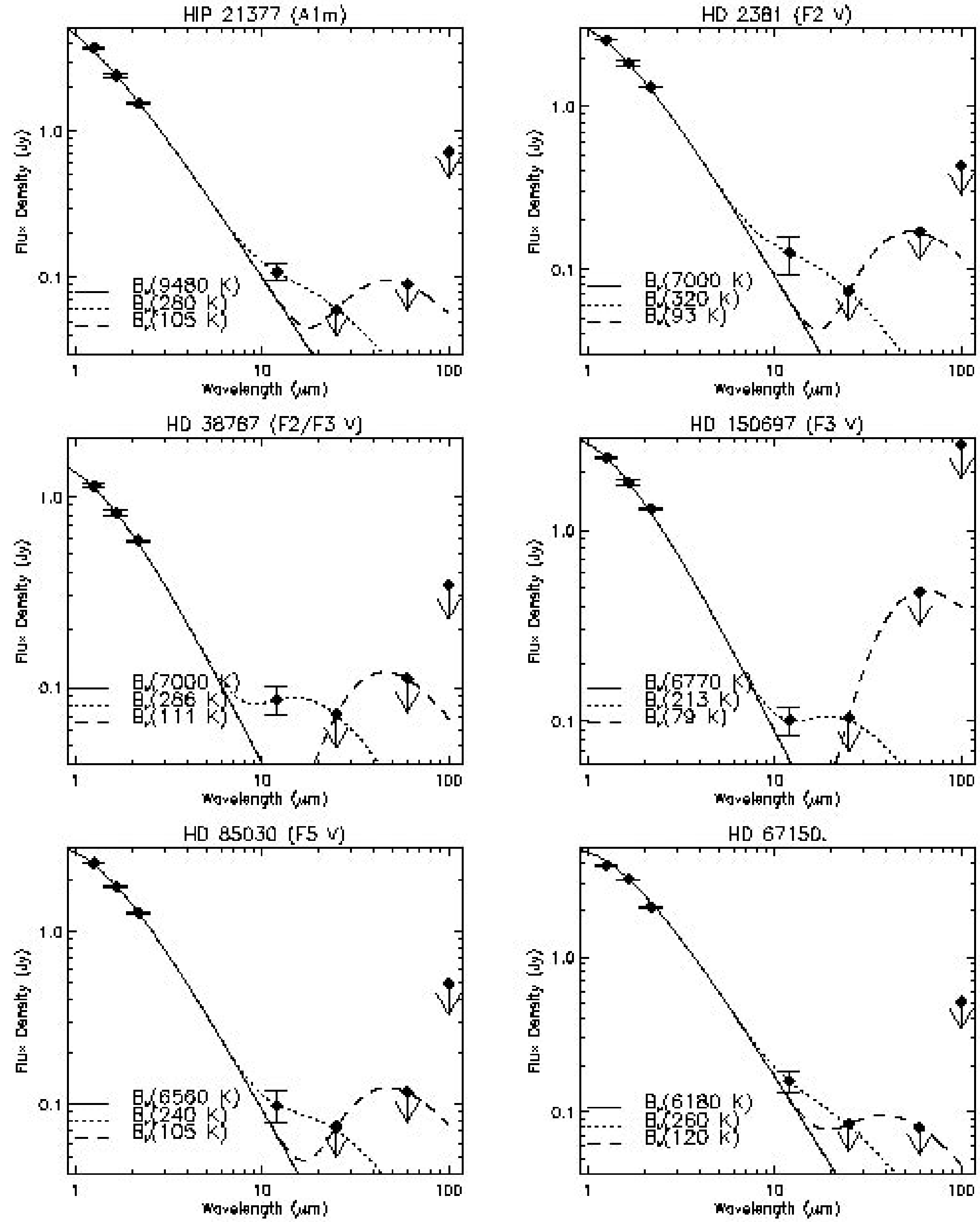
Status of The 2MASS Survey

- 2MASS is a near-IR all-sky survey
  - 3 bands @ J(1.2 μm), H(1.6 μm) and K_s (2.2 μm)
- 98% of sky has been surveyed from Northern and Southern telescopes (Mt. Hopkins and CTIO)
  - Operations end in Nov. 2000 (North) and March 2001 (South) followed by one year of final processing
- Performance meets or exceeds Level 1 requirements
  - 5σ sensitivity of (J,H,K_s) ~ (16.8, 16.0, 15.5 mag)
  - 2%-3% photometry for bright sources
  - Absolute positional accuracy of 0.2″, eventually 0.1″
- 48% of sky has been released publicly with 1,897,500 images; 162,213,354 point sources; and 585,056 galaxies


Star with excess
Normal star
Mean normal stars
Waters et al. 1987, &:
Koornneef 1983
Bessell & Brett 1988
B6
A4
F1
G3
K1
K3
M0
2.0
1.5
1.0
0.5
0.0
−0.5
0.0
0.5
1.0
2MASS K$_s$ − IRAS FSC [12] (mag.)
2MASS J − K$_s$ (mag.)

Properties of 2MASS Excess Stars

- Spectral types A1 to G5 V at distances ~100 pc
- Inferred dust temperatures 200-500 K implying orbital distances of 0.5-1 AU
  - Need longer wavelength data to constrain temperature and optical depth
  - Angular sizes of 0.01″ to 0.5″
- $\tau \sim 2\mathrm{x}10^{-3}$ to $7\mathrm{x}10^{-5}$ (10^4 to $10^3 \times$ solar system)



SIRTF Goals for Debris Disks

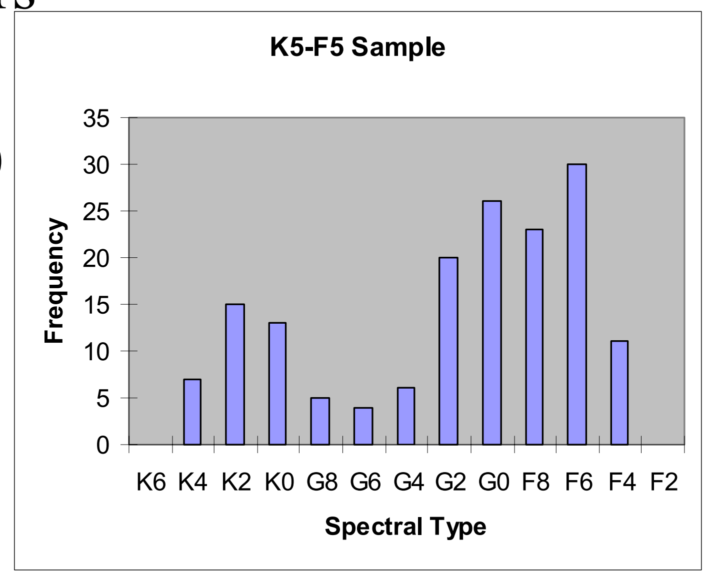
- Assess prevalence of debris disks as a function of spectral type and other parameters (age, binarity, planets) to a level 10-100 times more sensitive than IRAS/ISO
- Determine physical parameters of disks
  - Density and temperature distribution as function of radius
  - Fractional luminosity in dust
  - Dust composition
- Calibrate disk models using resolved images, spectral energy distributions (SEDs) of closest, brightest stars (10-20 stars)
- Make photometric and SED measurements of large sample (~200)
  - Use SED to infer density and temperature distribution as function of radius

SIRTF Debris Disks Samples

- The “Fantastic Four” and the “Dirty Dozen”
  - Spatial/spectral mapping
- Evolutionary sample of A stars
- Sample of Binary F stars
  - Broad range of orbital separations
- Volume Limited Sample of F5-K5 stars
  - Disk as function of age, binarity, spectral type
  - Stars with planets
- Nearby Stars
  - Disks and companions

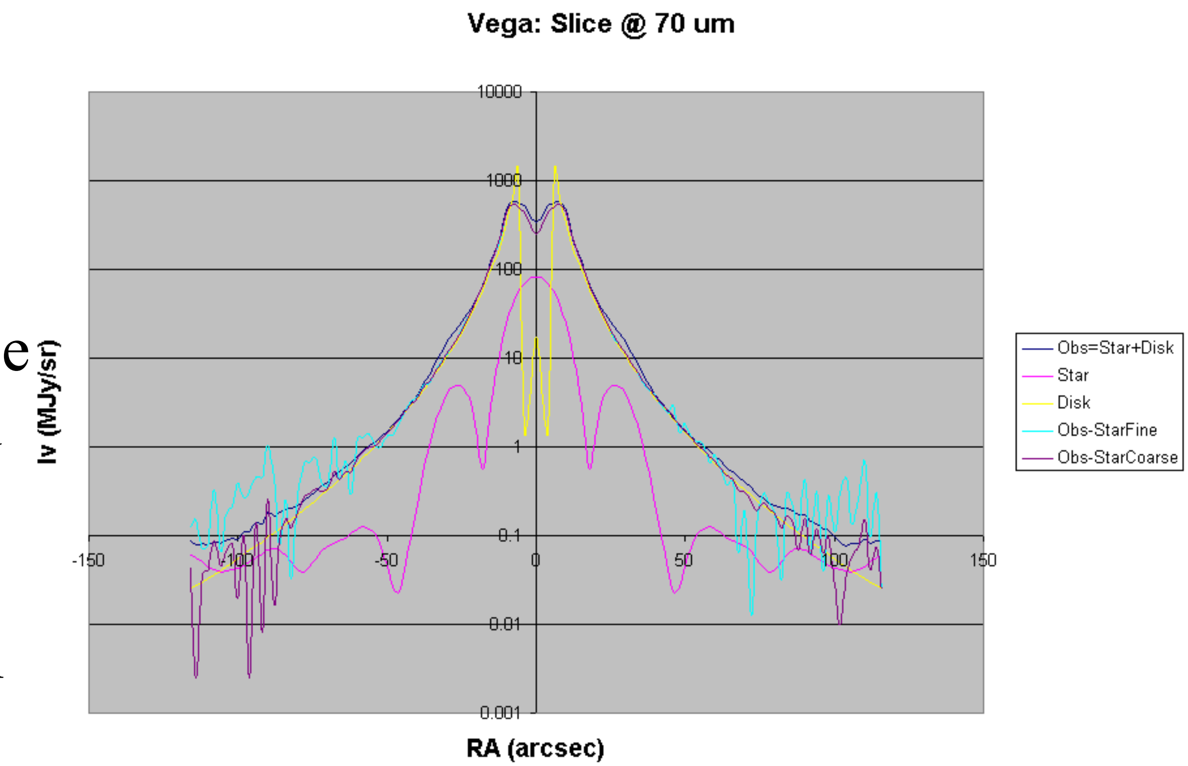
Volume Limited Survey

- Selection from Gliese Catalog
  - K stars within 15 pc
  - G and F stars within 25 pc
- Use IRAS/predicted fluxes, confusion and cirrus estimations to ensure clean sample
- Final observing lists includes ~ 150 stars
- Age estimates for ~half of sample Lachaume *et al.* 1999 (A&A, 348, 897)
  - X-ray and HK line strengths
  - Kinematics (e.g, Ursa Major group)
  - Isochrones
- Gaidos (1998) identified G-K stars, analogs of sun in heavy bombardment phase (<0.5 Gyr)

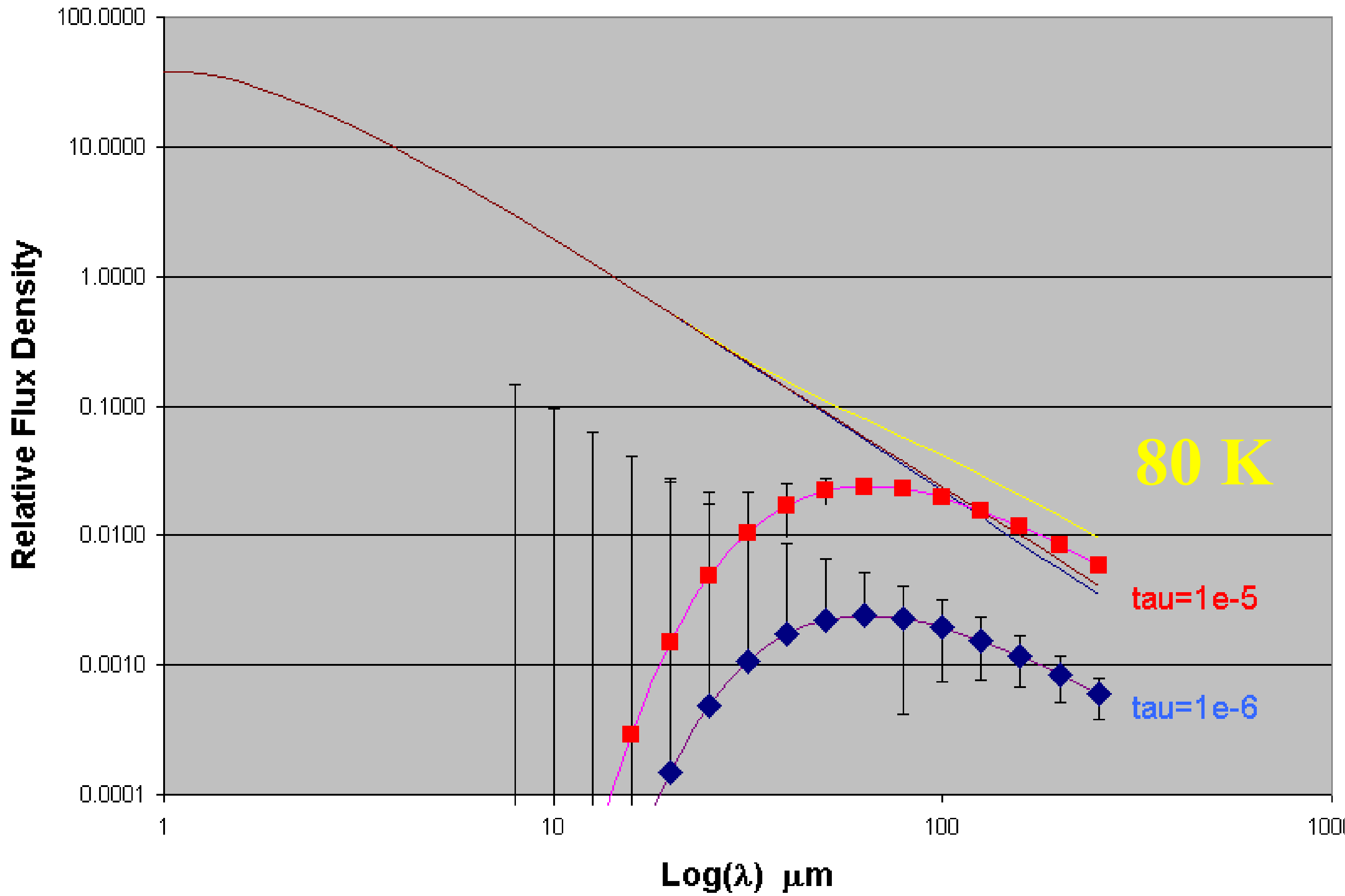


SIRTF is Resolution Challenged...

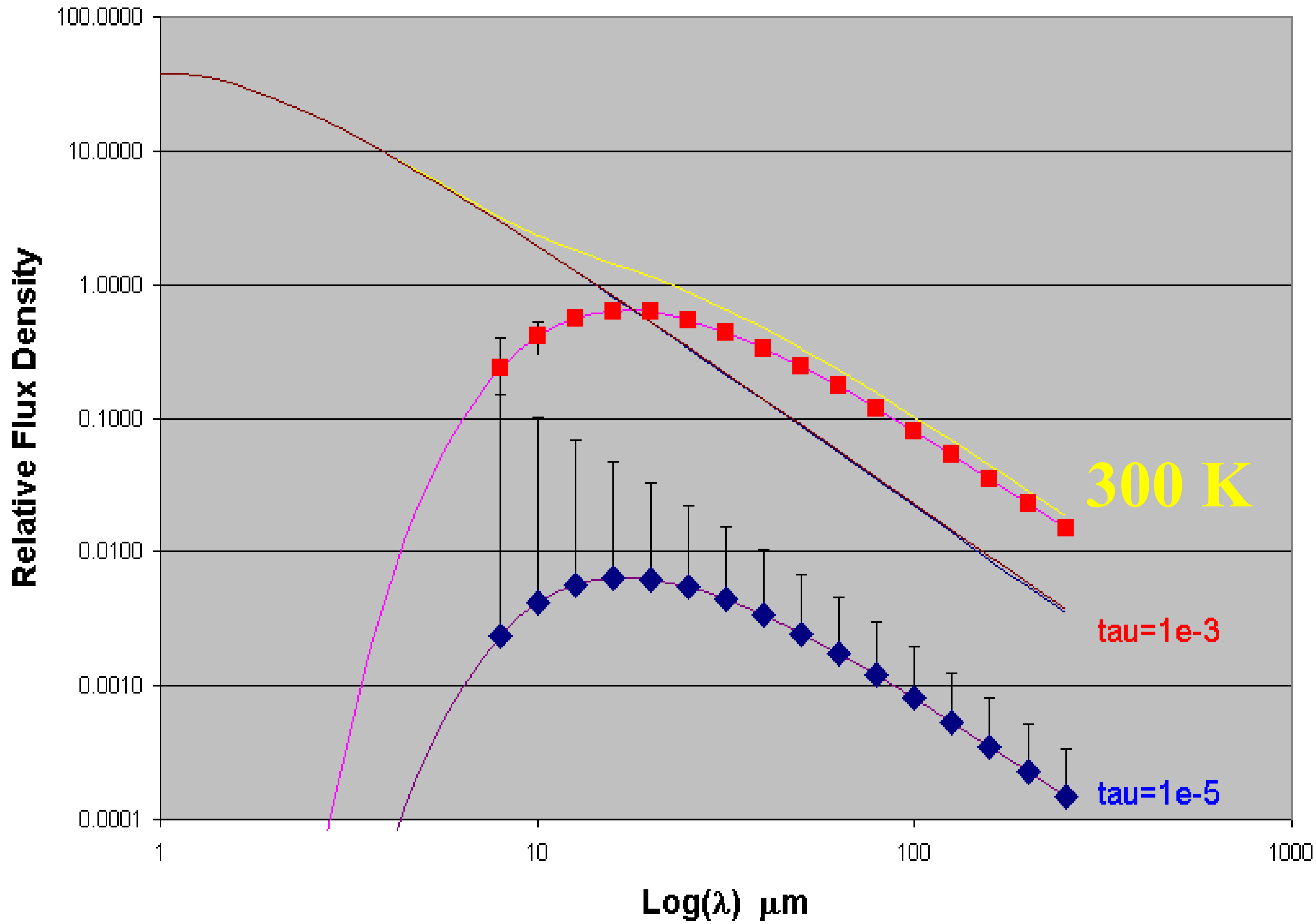
- SIRTF will resolve disks around only a few of the brightest, closest stars
  - Resolution limited to few to 10s of AU means best able to study "Kuiper belt" region
- Photometric accuracy limits SIRTF performance on non-spatially resolved disks
  - ~ 10× SS at 70 μm
  - ~100 × SS at 12 μm



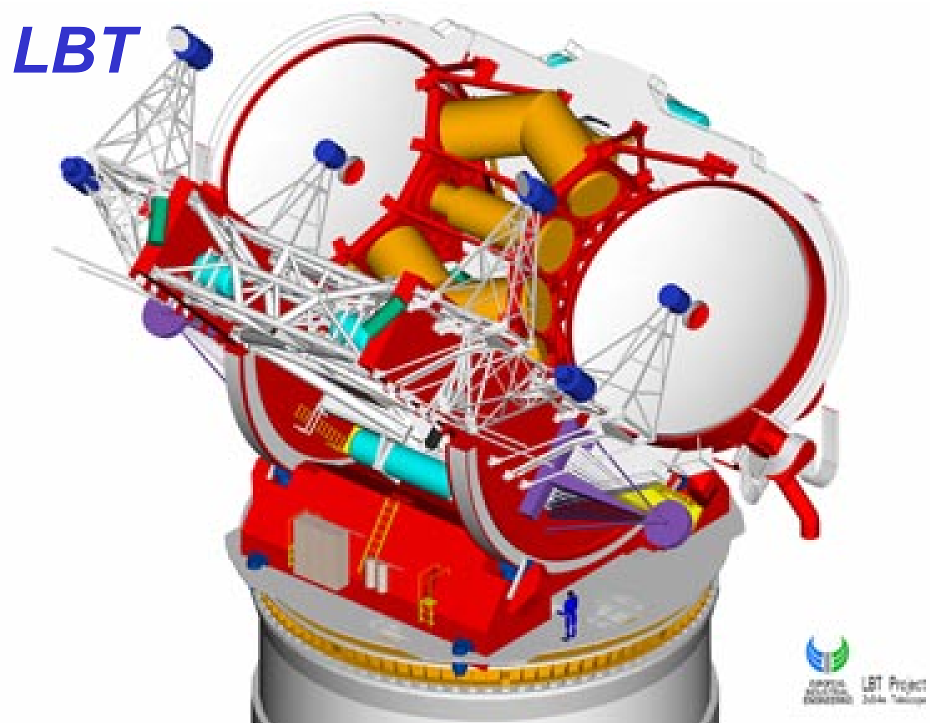
SIRTF Measures Kuiper Belts Well

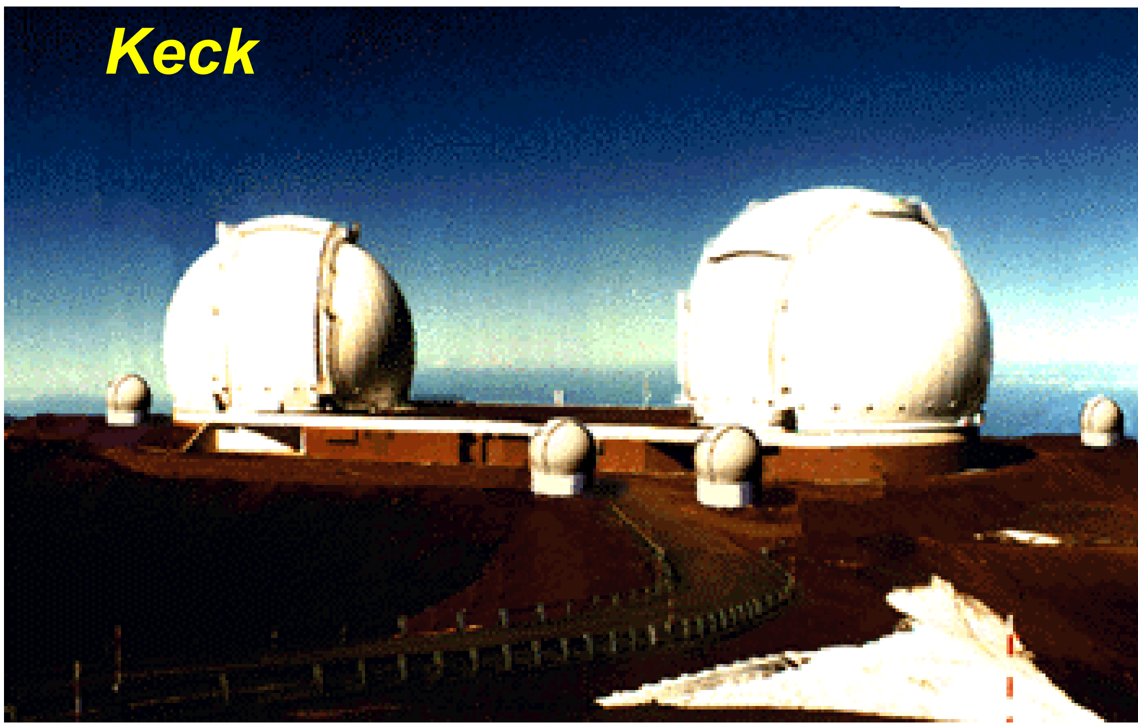


...But is Limited for Hot Zodi's...

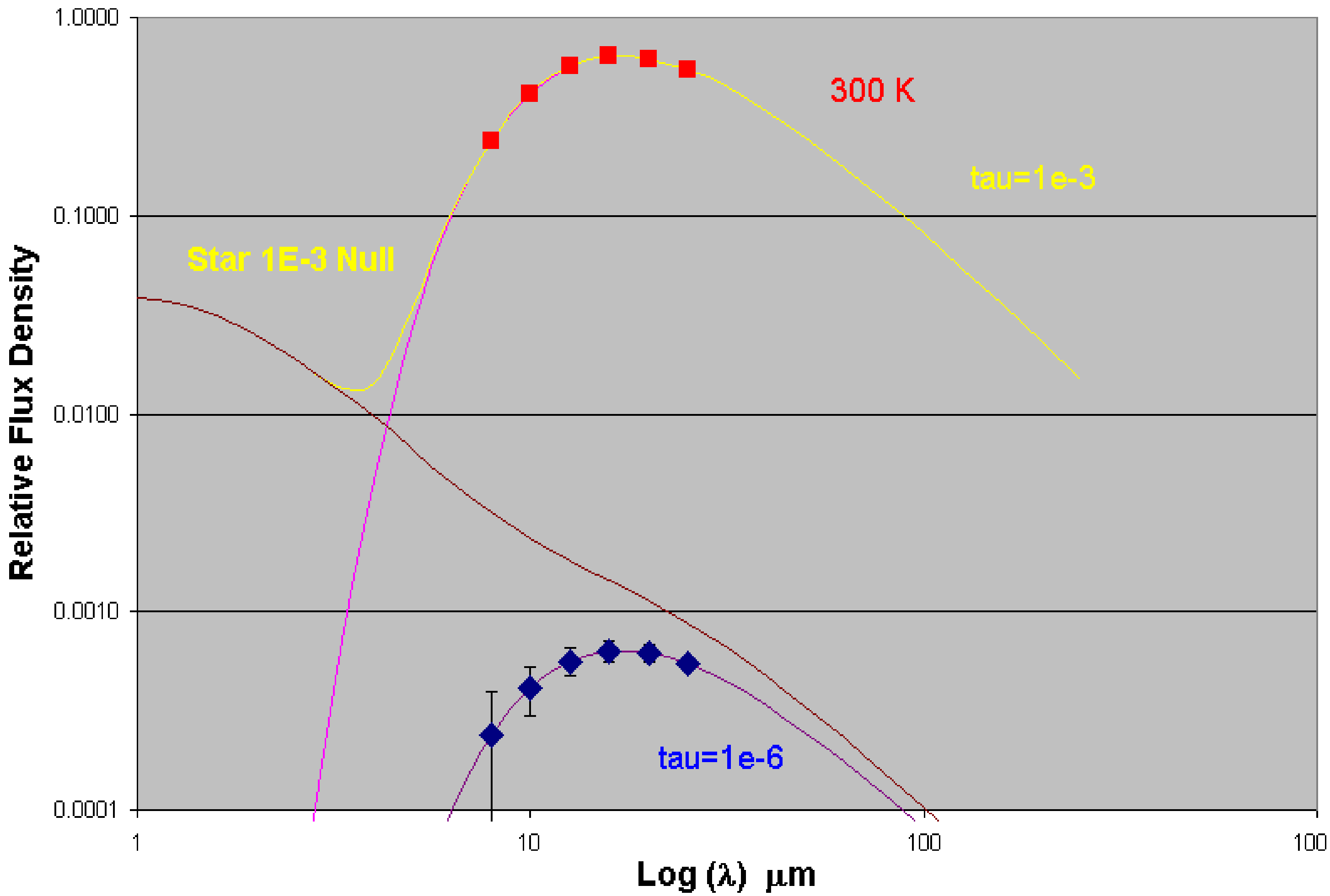


…But… Interferometers Can Use Spatial Resolution to Reject Star

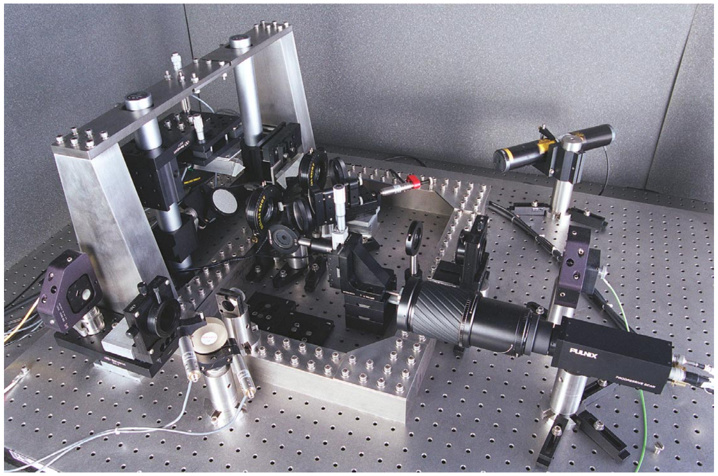




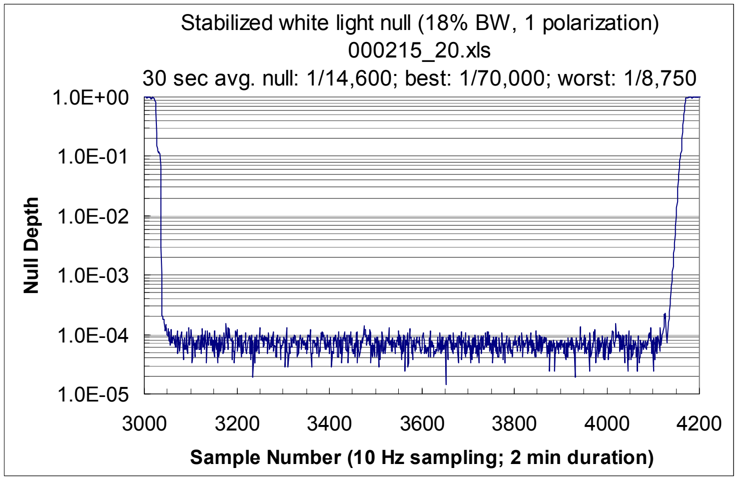
Nulling Can Detect Faint, Hot Zodis



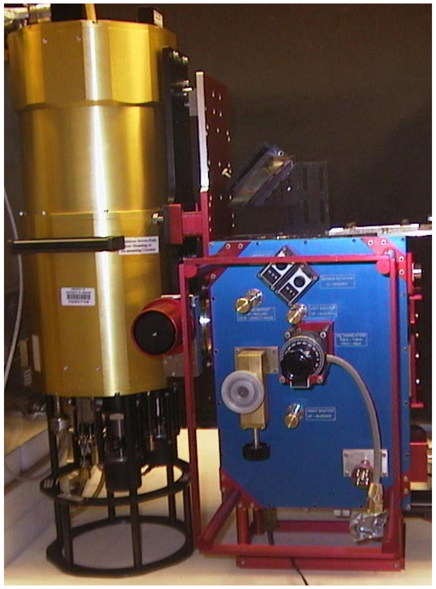
Progress on Starlight Nulling

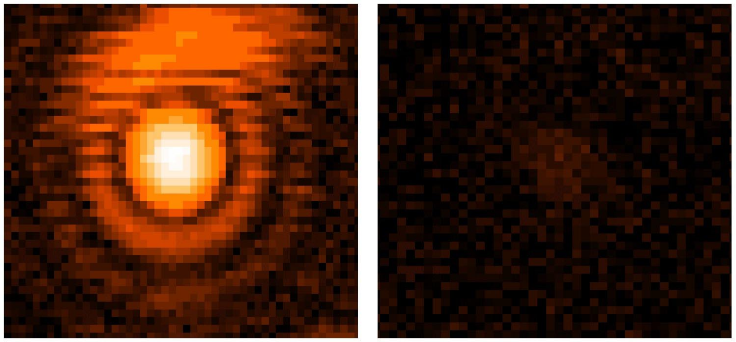


JPL Laboratory Nuller



1/14000 visible light null; 18% BW

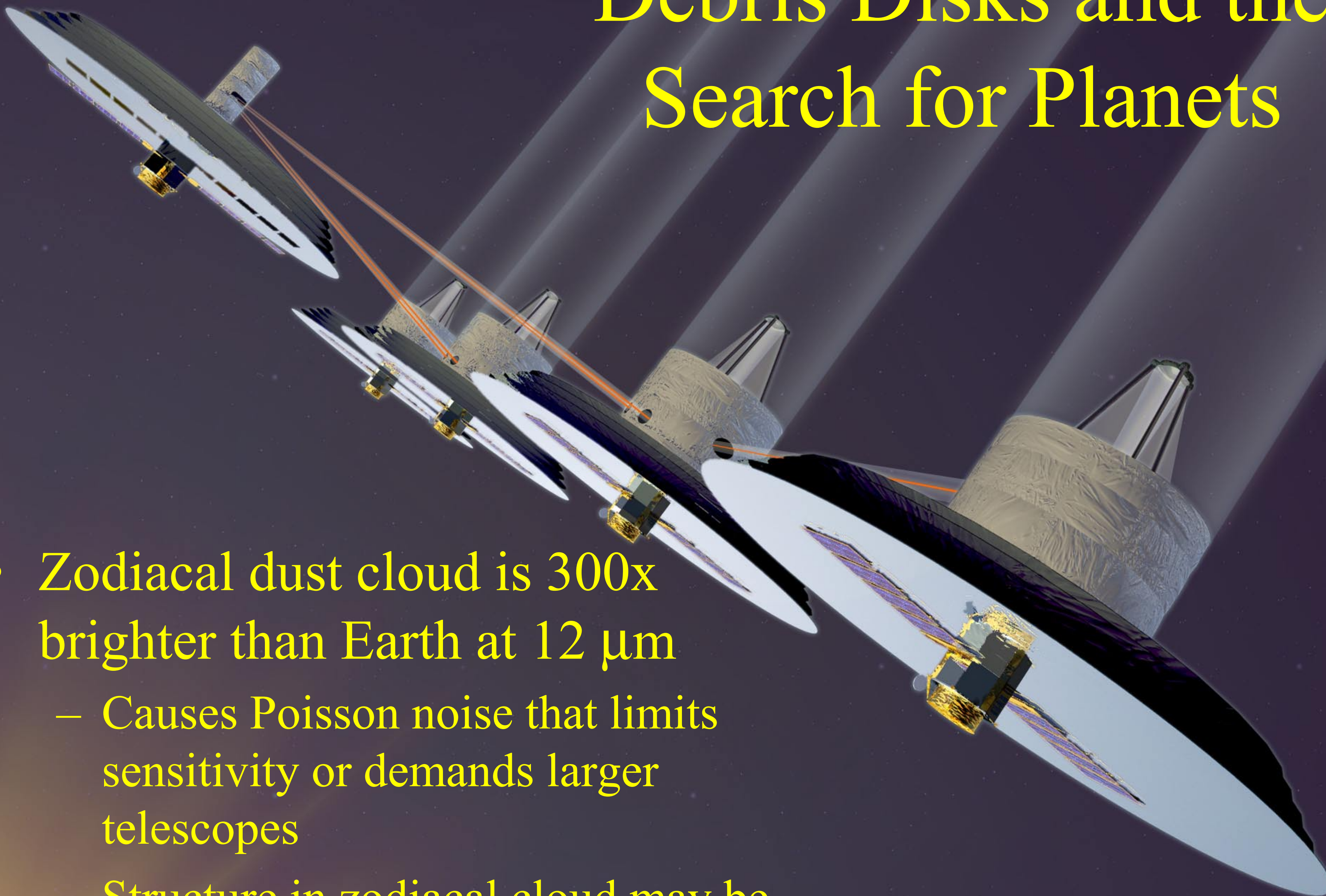




1/3500 IR null; narrowband 10μm CO_2 laser

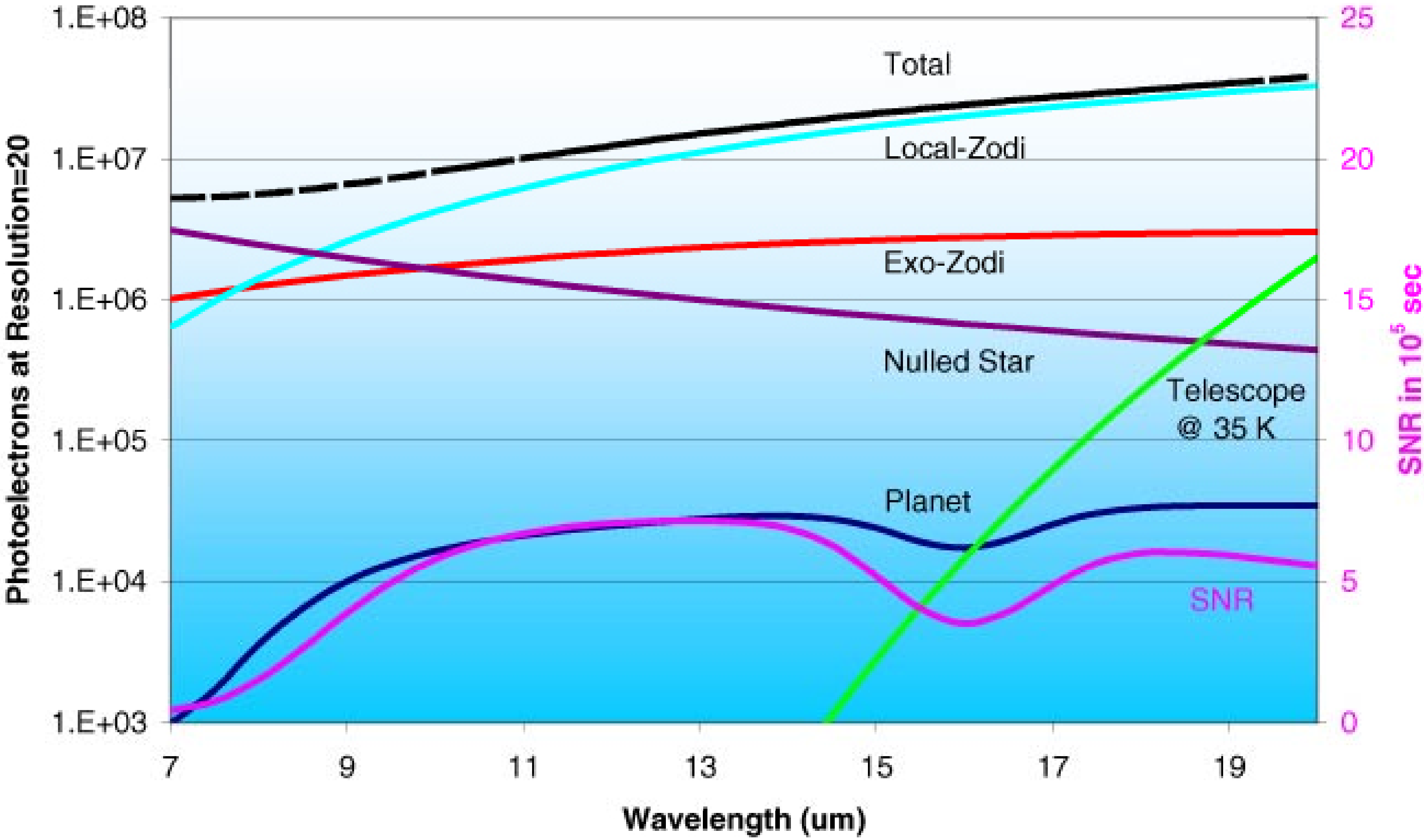
University of Arizona BLINC Cryogenic IR Nulling Camera

Debris Disks and the Search for Planets

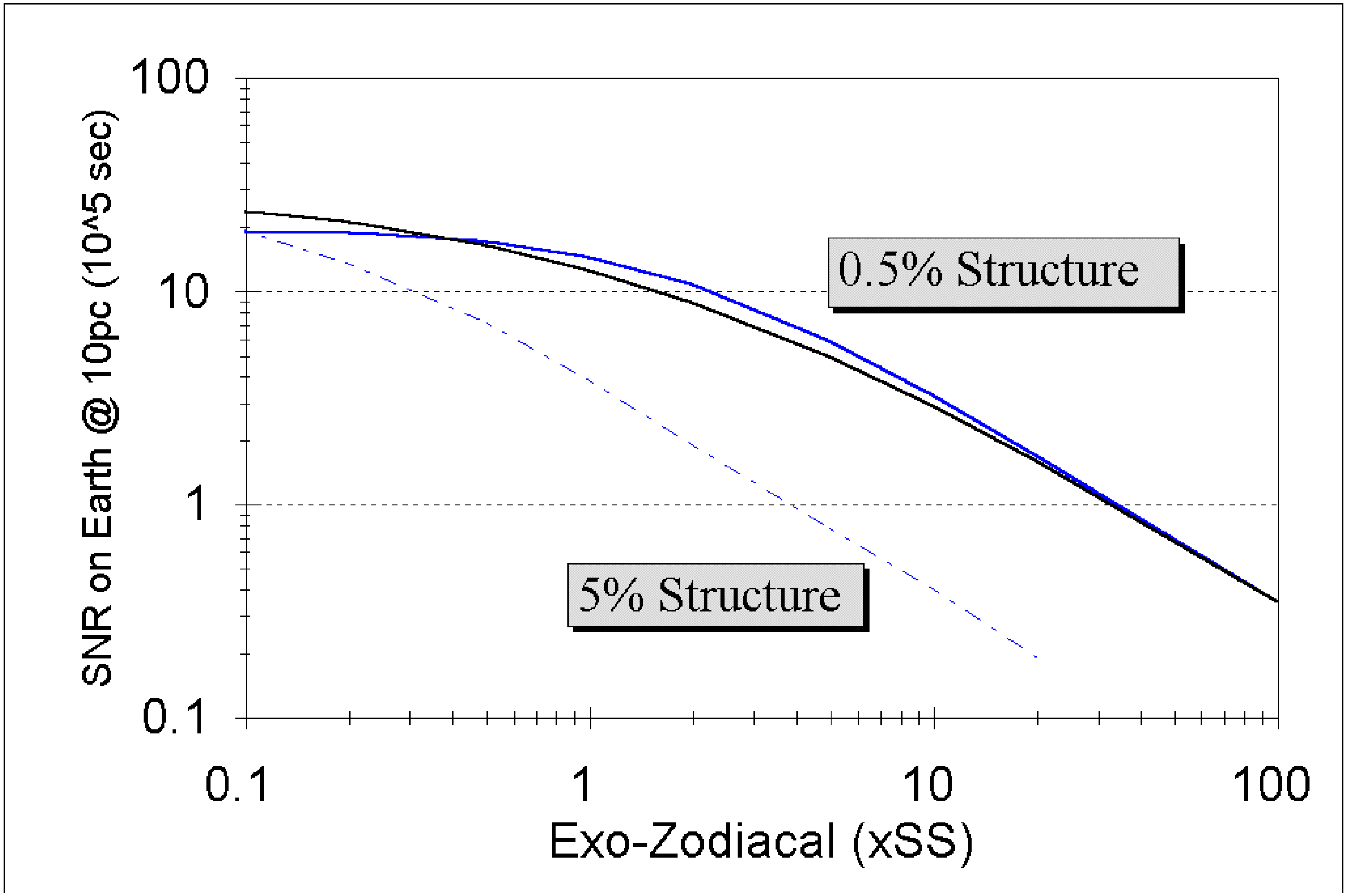


- Zodiacal dust cloud is 300x brighter than Earth at 12 μm
  - Causes Poisson noise that limits sensitivity or demands larger telescopes
  - Structure in zodiacal cloud may be irreducible noise source

TPF Signals Include Exo-Zodi



Exo-Zodi Masks Planets



Next Decade Will Revolutionize Understanding of Planetary Systems

- SIRTF will measure Kuiper Belts at solar system levels
  - Zodiacal clouds only to ~100x Solar System
- Keck Interferometer & Large Binocular Telescope will measure zodiacal clouds to 1~10x Solar System
- Keck-I, FAME, and SIM will complete census of planets
  - Giant planets over wide range of orbital parameters
  - Few Earth mass planets in < 1 AU orbits
- Together these datasets will elucidate the formation and evolution of planetary systems
- Identify stars suitable for searches for habitable Earth-like planets with TPF